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LEVEL II (2)

A GENERALIZED PROCEDURE FOR ASSESSING
THE INCLUSION/NON-INCLUSION OF
PASSIVE SOLAR TECHNIQUES
IN FACILITY DESIGN

Arthur R. Thayer, Captain, USAF

LSSR 79-81

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Consideration of inclusion of solar energy concepts into the design of new facilities is mandatory for Air Force planners under current public law. Some guidance has been provided to Air Force planners, mainly within the Life-Cycle Costing Manual for the Federal Energy Management Programs. However, no complete procedure exists for performing an economic feasibility study of passive solar concepts. This thesis proposes a procedure for assessing the economic feasibility of passive solar concepts versus conventional construction. Utilizing the proposed procedure, an actual study was done for the proposed MX MFH units. The study revealed that a conventionally designed MFH unit had a lower life-cycle cost than the analyzed passive designs, over the facility's projected 25 year life. The procedure utilized for the actual study was used as a guide to identify the factors that an Air Force planner needs to make sound fiscal decisions on the inclusion/non-inclusion of passive solar techniques in facility designs. One passive concept not investigated due to insufficient data was the so-called double-shell design, which, if functions as claimed, would eliminate the need of any heating or cooling equipment. Elimination of this equipment could quite possibly make this passive concept economically feasible for facility designs.

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A GENERALIZED PROCEDURE FOR ASSESSING THE INCLUSION/NON-INCLUSION OF PASSIVE SOLAR TECHNIQUES IN FACILITY DESIGN

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

By

Arthur R. Thayer, BS
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This thesis, written by

Captain Arthur R. Thayer

has been accepted by the undersigned on behalf of the Faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING MANAGEMENT

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CHAPTER I

INTRODUCTION

Problem Statement

Currently no method has been developed or adopted by the Air Force to assess the feasibility of including Passive Solar technology in the design of a structure versus the selection of conventional construction. However, the federal government requires the Department of Defense (DOD) to utilize solar energy systems for facilities whenever it is cost effective, according to SEC. 901., Section 2688 of Title 10, United States Code. Work has been done on some aspects of a passive solar feasibility study. Nevertheless, a procedure for performing a complete passive solar feasibility study has yet to be adopted within the Air Force.

Because of this situation, there exists a need for a procedure to be developed for such decisions as those which must be made for the design of MX facilities by the Air Force Regional Civil Engineer (AFRCE) MX and the Strategic Air Command (SAC) Facilities Requirements offices. The development of such a procedure will allow determination of the design for a particular facility that results in the least life cycle costs. This determination along with the performance of such a feasibility study will allow such offices as those aforementioned to make an intelligent decision on what design is to be actually implemented.

Background

The United States Air Force is currently on the brink of the single largest construction project it has ever undertaken. In addition, the project is one of the largest undertaken by the United States government. This project is the MX Intercontinental Ballistic Missile (ICBM) system that has an accompanying price tag currently estimated at $30 billion (5:3).

To deploy this massive system requires care in the determination of a method for basing the weapon system. Two basing modes are currently undergoing consideration for the actual deployment of the system. These two modes are sea basing and land basing. Of the two modes, the majority of work to the present has been concentrated on the land basing concept. To this end, an AFRCE MX office at Norton AFB and a special Facilities Requirements office at Offutt AFB, Headquarters SAC, have been established.

The AFRCE MX and the Facilities Requirements offices are responsible for the design and development of the facilities required to support the MX system. A substantial portion of the facilities required to support the MX system is the Military Fmaily Housing (MFH) to be constructed in support of the missile system. Current estimates for the number of MFH units for the two operational bases currently planned are 4200 and 2900 units, respectively (18:1).

The most probable locations for the two bases are currently Beryl, Utah and Ely, Nevada (1:7). Other locations also being considered are likewise located in the southwestern United States (1:7).

Because of the projected locations of these bases, the availability of renewable energy resources in this region, and the United States' current energy situation, common sense dictates the exploration of using renewable energy resources in the design of the facilities, including the MFH, to support the MX system. In further recognition of this situation, the use of renewable energy systems to meet the MX missile system energy requirements has been established by DOD and the Department of Energy as a main objective to be met within the MX construction project (14:2).

Justification

One of the renewable energy resources that is a relatively new field of technology is passive solar energy. Only this year has the Air Force begun to teach passive solar design techniques, with these Air Force Institute of Technology resident Graduate Engineering Management (GEM) students not scheduled to graduate until September 1981. Passive solar design is the incorporation of passive solar concepts, which use the natural energy flows within a structure, to meet the heating needs of that structure. Also, the School of Civil Engineering at Wright-Patterson AFB offered its first class on the subject in March 1981. This situation limits the expertise of Air Force personnel within the passive design field to those who have taken courses in self-study efforts or new graduates who have had a passive solar design course in their formal curriculum.

In checking with the AFRCE MX and Facilities Requirements offices, the researcher discovered that there was no expertise in the passive field available at these offices (18:1). Current plans call for an Architect and

Engineering (A&E) contract to be let to accomplish the design work on the MFH units as well as the other base facilities (18:1). The A&E contract calls for the exploration of various renewable energy sources in the design of facilities. This clause is included in the contract in accordance with the previously cited United States Code.

Final review and acceptance of the plans received from the A&E firm is the responsibility of the two offices aforementioned. This fact creates the situation of Air Force engineers evaluating and accepting a design/study which they do not have the necessary technical expertise to perform themselves.

Definitions

At the start of this research, it is important to define several terms so that a common frame of reference can be established for the reader. The following words will be used as defined:

1. Passive solar system: a heating or cooling system for a building or residence in which the thermal energy flows in the building structure are by natural means, such as, radiation, conduction, or natural convection (17:28).

2. Direct gain system: a passive solar system that uses sunlight to directly heat the actual living space as shown in Figure 1. For this system to perform as intended, sufficient mass must be exposed to the sunlight to store enough daytime heat for release during cold winter nights. This mass is usually composed of masonry or water (17:29).

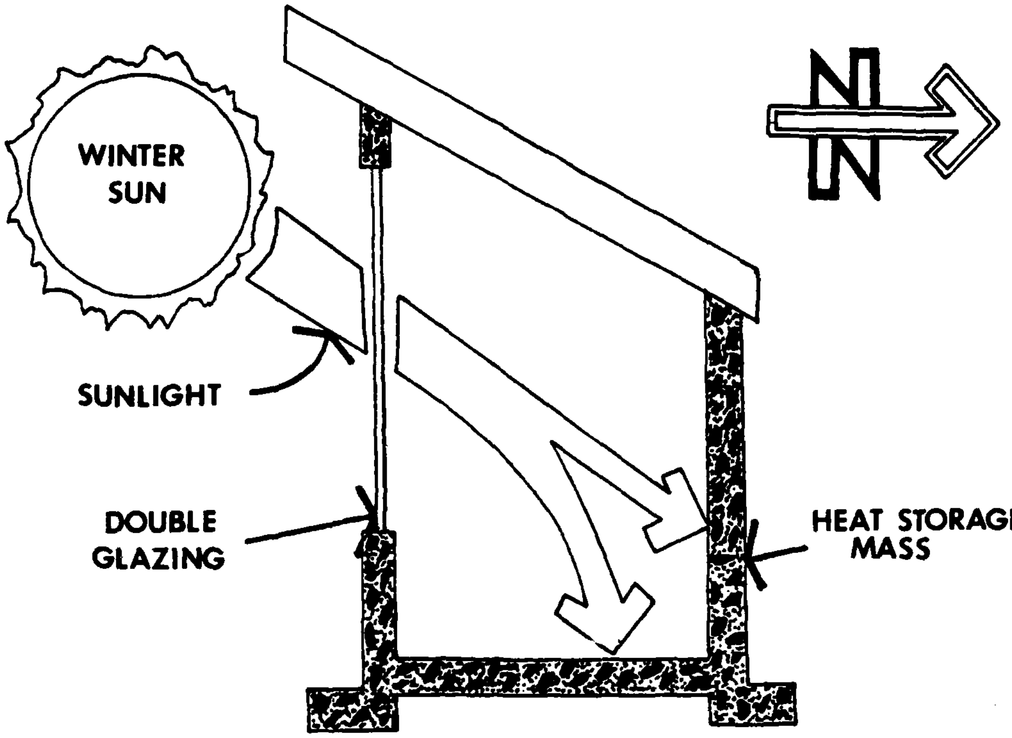


Fig. 1. Direct Gain System in Northern Hemisphere

3. Indirect gain system: a passive solar system that employs a mass located between the actual living space and the sun (17:43). This mass absorbs the sunlight and transmits the converted thermal energy to the living space during the cold winter nights. The mass usually takes the form of a thermal storage wall or roof pond. An example of a thermal storage wall is shown in Figure 2.

4. Combined system: a passive solar system that incorporates a combination of direct and indirect gain systems. An example of a combined system is shown in Figure 3.

Research Objectives

The objectives of this research effort are (1) to determine the economic feasibility of incorporating passive solar concepts in the design of new facilities, such as the projected MFH units for the MX missile system, and (2) to develop a generalized procedure for extending this analysis to future USAF construction projects. This procedure will enable USAF engineers to meet the feasibility study requirements levied within the Military Construction Authorization bill for Fiscal Year 1981.

Research Question

The question concerning the design of facilities, such as the MFH units for the MX, that is addressed in this effort is:

What factors should be included in a generalized procedure to enable Air Force planners to make fiscally sound decisions concerning the inclusion/non-inclusion of passive solar techniques in facility designs?

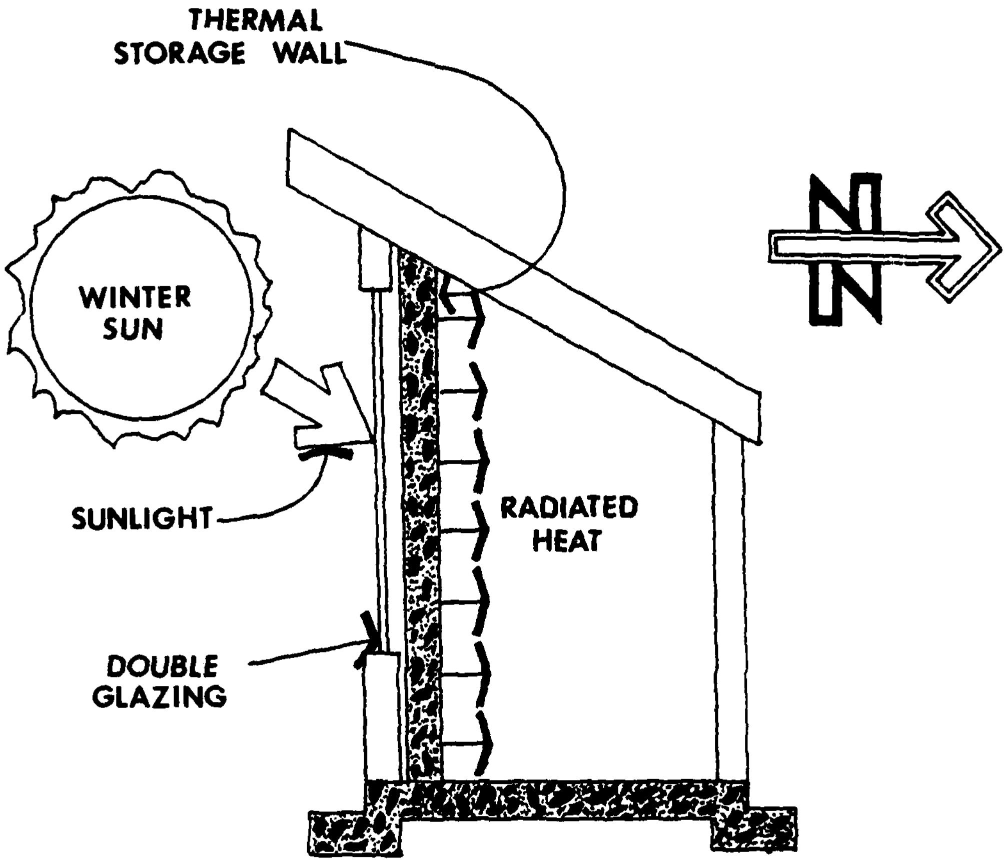


Fig. 2. Indirect Gain System in Northern Hemisphere

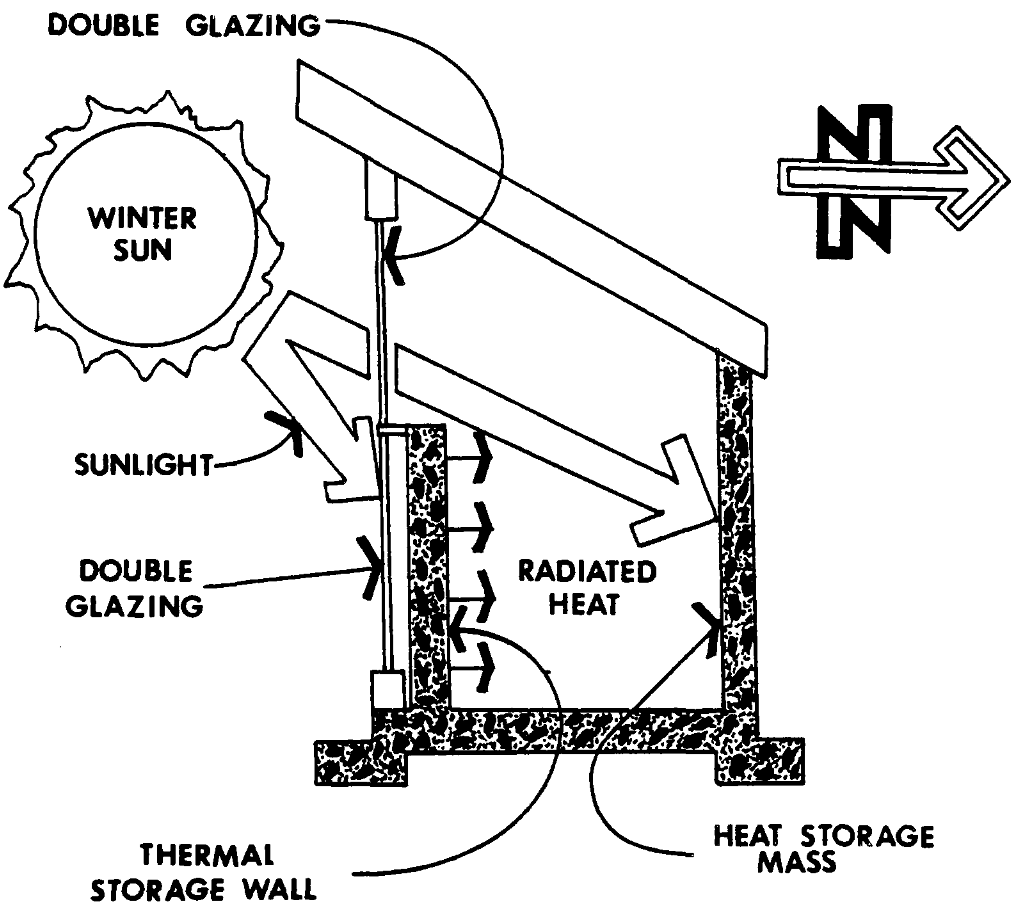


Fig. 3. Combined System in Northern Hemisphere

CHAPTER II

LITERATURE REVIEW

The problem identified for this study was to evaluate the economic feasibility of incorporating passive solar design techniques in the design of facilities, particularly the MFH units projected for the MX operational bases. Considerable research has been done in the area of estimating energy cost savings of structures. However, methods for estimating the differential construction costs between a passive solar design and a conventional design have not received much attention. A review of the available material in these areas will help form a basis on how to solve the identified problem.

In September 1978, Brandt Anderson and Ronald Kammerud presented a thesis concerning the determination of energy savings for passive solar buildings. This study addressed the issue of determining actual energy savings in a passive structure.

The problem addressed by their study is the actual determination or estimation of these savings. To determine exact amounts would require the actual construction of a passively designed building and a conventional counterpart. However, in most cases this is not a feasible alternative due to costs. Therefore, their study attempted to verify the feasibility of simulating a conventionally designed structural counterpart on a computer using the building loading requirements for estimation of energy savings by the passive design.

The method employed in the study incorporated taking actual energy usage measurements in a passive solar structure. These measurements were then compared with those of a conventional structure. This conventional structure, termed a crippled passive structure, consisted of a design with the same functional floor plan, and which is designed, constructed, and used with an emphasis on energy conservation that is consistent with the non-passive features of the passive solar structure (4:7). The crippled structure is merely the passive structure with its passive features replaced by conventional construction features consistent with the non-passive features of the passive structure. The difference between the two energy amounts projected to be used by each structure is the savings resulting from the passive design. This process was reiterated until energy costs were minimized.

The results of their study show that their method provides realistic results, but with the following three limitations. The first limitation is the efficiency of the auxiliary system. To prevent a multiplicative error effect, required the application of the same system efficiencies. That is, the auxiliary systems selected had to be technologically mature systems so that their efficiencies were well known and accepted in industry (4:18-19). In this manner, if the efficiency differs from the actual efficiency by 5-10 percent, then the error is only that amount (4:19).

Another limitation is the effect changing weather causes in the calculations. Degree day calculations are dependable if:

1. A proper base temperature is used and,

2. The study period is limited so that the range of weather experienced could not include a seasonal variation.

When these two requirements are met, the loading requirements for the non-passive building will yield energy usage results which are not appreciably in error as a result of the weather (4:19).

The final limitation is that not all thermal effects can be modeled in sufficient detail. To minimize this source of error required normalization of the crippled passive structure. The accuracy of the correction was determined by the ability of the energy calculation technique to analyze the specific features of the crippled passive structure. To assure the technique's effectiveness, the crippled passive model must reflect the measured crippled passive structure characteristics as closely as possible. In other words, the crippled passive model and the conventional building are defined and modeled to be as physically similar to each other as possible.

The authors recommended that further research be conducted to determine mass effects, infiltration estimates, and slab heat losses. The authors believe that the currently available material in these areas is incomplete, and in some cases, insensitive or inaccurate.

Also, in September 1978, Marlo Martin and Paul Berdahl presented their research effort on radiative and passive cooling to the 3rd Annual Solar Heating and Cooling Research and Development Contractor's Meeting in Washington D.C. The purpose of their research effort was to assess the infrared radiative cooling resource in order to determine the extent to which radiative, convective, and evaporative cooling can supplement or replace refrigerative type systems for the space cooling of buildings.

However, their research study was mainly a preliminary research effort and only served as a beginning point for further work toward developing a passive cooling system to replace refrigerative type systems for space cooling of buildings. The infrared sky radiation measurements obtained from this research effort will provide the information necessary to develop such a system.

In January 1979, Deborah L. Buchanan, representing the Solar Energy Research Institute, presented a research study that reviewed the economics of selected passive and hybrid systems. A hybrid system being one that combines the use of both active and passive systems. The author reviewed fifty passive designs of four basic types: (1) direct gain, (2) indirect gain, (3) isolated gain, and (4) hybrid.

Within the review, the author presented figures on the various building load ranges, collector area ranges, performance, percent solar contribution, cost both maintenance and capital, and cost effectiveness. From the data presented within the report, the author made several conclusions. The first is that cost and performance for the various generic designs vary widely due to design and climate variations. Another conclusion is that actual system performance usually matches or exceeds that of the simulated system. Keeping this study in perspective, the author did include one caution, the data base was small and the results should therefore be regarded tentatively.

In May 1980, Major Marion A. Pumfrey and Major John W. Thilgen presented a report concerning the cost effectiveness of passively heated/cooled solar housing. In their report the authors set out to develop a mathematical model for a passively heated/cooled solar house.

To develop their model, the authors first developed what inputs affected the effectiveness of the passive system. In their model, there were five inputs. They are meteorlogical data, solar energy delivered, energy demand, storage state, and the state of the internal environment. These five inputs were calculated in order on an hourly basis until a full year had been completed. From this information the annual cost was computed.

This information was then used in a life cycle cost analysis. Their analysis included the initial investment, salvage value, replacements, energy, property tax, property tax tax deduction, interest tax deduction, maintenance, insurance, and the value of the building space. Included in their report, the authors wrote a computer program to lead a person through the entire process of maximizing the cost effectiveness of the passive system. However, nowhere did the authors make any attempt to substantiate that the program did indeed do what it was intended to do. Also, as can be seen from the cost analysis portion of the program, the report's efforts are designed for use in the civilian community and not for the governmental environment where taxes and insurance are not applicable.

In June 1980, Second Lieutenants Gary D. Transmeier and Albert P. Allan presented a thesis that reviewed the methods that analyze passive solar systems. In their thesis the authors sought to recommend, based on the needs of the Air Force, an analysis technique for passive system design within the Air Force that could be easily done by hand.

To develop a sound recommendation the authors established a scoring model that incorporated six basic criteria that they believed to be important. These criteria are performance, economics, flexibility, usability, implementation, and computing device. Each criteria was completely defined so that each hand calculation method addressed in their thesis could be analyzed on an equal basis.

The actual scoring was done on a point basis of either 1, 2, 3, or 4. A "1" was given if the method did not contain the criterion and was not modifiable. A "2" was given if the method did not contain the criterion, but could be modified with difficulty or at high cost. A "3" was given if the method did not contain the criterion, but could be easily and inexpensively modified. A "4" was given if the criterion was wholly contained by the method.

The criteria were weighted, such that the applicable weight was multiplied by the score for a particular criterion. The results of the multiplications were then summed to provide an overall index. The method with the highest index became the recommended "best" package.

The results of the study showed that the "best" methods were the Rules of Thumb "Patterns" method and the Passive Solar Design Handbook method. Their overall scores were 12.3 and 12.9, respectively. To differentiate between these two methods, the authors performed a subjective comparative analysis. From this analysis the authors chose the Passive Solar Design Handbook method, basically due to its lower cost to the government and the supposed advantages of the Solar Saving Fraction (SSF) used in the Handbook method over the Solar Heating Fraction used in the "Patterns" method.

The authors recommended that further research be done in this area so that a complete program can be established throughout the Air Force. Additionally, they believe that the method of analysis should be reviewed every five years to ensure that new developments in the field of passive solar systems are incorporated into the Air Force's analysis method.

Summary

In summary, this literature review has presented the most pertinent material in the related area of this research effort. Each of the research efforts in some manner dealt with some aspect of this topic. However, none of them dealt completely with this research. The researcher believes this to be the first thesis that specifically analyzes how to develop comparative life cycle costs for passive solar versus conventional designs in detail.

CHAPTER III

METHODOLOGY

The purpose of this chapter is to describe the methods used to resolve the research question stated in Chapter I. The research was divided into seven basic phases, which are:

1. Overall approach
2. Data collection plan
3. Model development
4. Data analysis plan
5. Scope
6. Assumptions
7. Limitations.

Overall Approach

The overall approach chosen for this economic feasibility study was the accomplishment of a life cycle cost analysis. This approach was selected because life-cycle cost analysis is required for facility design decisions within Subpart A of Part 436 of Title 10 of the Code of Federal Regulations (22:iii). Use of life cycle cost in a economic feasibility study will therefore provide a meaningful comparison between the passive solar designs and a similar conventional design.

To answer the research question, a life-cycle analysis was performed for the designs of the MX MFH units. The procedure identified in this example was used as a basis for a procedure that can be generalized to other passive versus conventional design decisions. The generalized procedure will also omit any components in the example that are determined to be unnecessary. Also, any additions deemed necessary due to shortcomings in the example will be included.

Pumfrey and Thilgen's report identified the necessary components of a life-cycle cost analysis within the civilian community. These components are initial investment, salvage value, replacements, energy, property tax, property tax tax deduction, interest tax deduction, maintenance, insurance, and the value of the building space (19:29). However, for a life-cycle cost analysis in the DOD environment, the list of necessary components can be narrowed to initial investment, energy, and maintenance costs. Maintenance costs were eliminated because of the similarities of the designs. Since passive designs have few moving parts to wear out or need replacement, any differential maintenance costs should be minimal.

To determine the initial investment and energy costs, and then actually perform a life-cycle cost analysis required the accomplishment of six basic steps. These steps are : (1) accomplishment of the designs to be analyzed, (2) computation of energy requirements, (3) auxiliary heat load requirement determination, (4) differential initial investment cost computations, (5) life-cycle cost analyses computations, and (6) comparison of life-cycle cost analyses. A flow chart depicting these steps is shown in Figure 4.

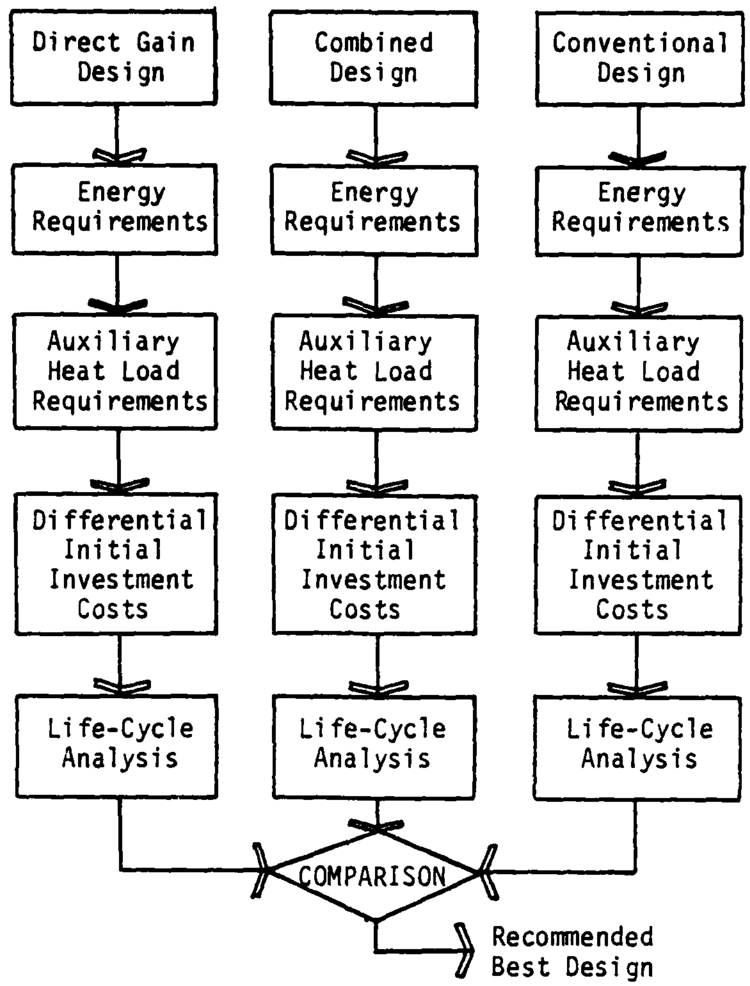


Fig. 4. Study Computation Flow Chart

The first step of the study established a rough structural design for each passive technique identified in Chapter I, except for indirect gain. This technique was omitted, because the researcher believes the lack of windows inherent in the technique would be unacceptable to the occupants. In addition to the passive designs, a rough structural design was accomplished for a similarly configured conventional structure. For these designs to be meaningful to Air Force planners, they include requirements levied by Air Force or DOD regulations or manuals and additionally, any special features needed or desirable due to the climate at the facility's proposed location. The conventional design incorporates the same functional floor plan with features consistent with the non-passive features of the passive designs (4:7). This similarity will help ensure the meaningfulness of the comparisons.

The second step of the study involved the determination of annual energy requirements for each passive design as well as the conventional designs. To determine the energy requirements involved the determination of heat losses through the exterior envelope of the structure and any internal heat gains to the structure. Additionally, for the passive designs the amount of heat gained by the passive systems and delivered to the structure was computed to identify the structure's auxiliary heating requirements. The auxiliary heating requirements being the amount not supplied by the passive system.

The study's third step determined the auxiliary heat load requirements, which were needed for sizing the auxiliary heating system for the structure. The size of the auxiliary heating system allowed a determination of the investment costs required for the system. The initial investment costs were then computed for each design. As stated earlier, only differential costs were considered. In other words, only components that differed from one design to another were considered in the study, including items such as: gypsum board, paint, framing members, masonry, concrete, heating system, and insulation.

The study's fifth step incorporated the information gathered in the preceding four steps into a life-cycle cost analysis for each design. This analysis required the use of the time value of money concept, since the energy costs occur over the life of the structure. The time value of money concept as used within the Life-Cycle Costing Manual for the Federal Energy Management Programs incorporates not only the concept of opportunity costs, but also the concept that energy prices are rising at rates different than the general level of prices (22:38). These differential changes are termed escalation rates and are used to adjust the 7 percent discount rate established by the Office of Management and Budget (OMB) Circular A-94 (22:39). The 7 percent discount rate corresponds to what the government believes its investments should return to reflect the probable return of the investment if left in the private economy.

Within the Life-Cycle Costing Manual for the Federal Energy Management Programs, different escalation rates have been projected for three time periods. The time periods are mid-1980 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The appropriate adjusted discount rates were then used to translate energy costs from one point in time to the project start in 1985 (18:1).

To translate the energy costs through time required the use of two basic engineering economy equations. These equations are:

1. $P = A \frac{(1 + i)^n - 1}{i(1 + i)^n}$

2. $P = F \frac{1}{(1 + i)^n}$

where: A = annual amount

F = future amount

i = adjusted discount rate

N = number of periods to be discounted

P = present worth.

These equations are more commonly known as the series Present-Worth Factor (uniform series) and the Present-Worth Factor (single payment), respectively (20:164,168). These factors are sometimes shown in their shorthand version, which is: (P/A, i, N) and (P/F, i, N) (20:164,168).

In the final step of the study, the life-cycle cost for each design was compared to identify the design with the least life-cycle cost. The design with the least life-cycle cost is the recommended design for the MX MFH units.

Data Collection Plan

Data collection for this research included material from both primary and secondary sources. Data for accomplishing the necessary designs was derived from The Passive Solar Energy Book, Cooling and Heating Load Calculation Manual, Building Construction Illustrated, Regional Guidelines for Building Passive Energy Conserving Homes, and Air Force Manual 88-25, Family Housing Design.

Data for determination of the energy requirements of each design was obtained from five sources. The sources are Engineering Weather Data, The Passive Solar Energy Book, Cooling and Heating Load Calculation Manual, the M-X/RES Information Package, and the designs accomplished in this study. Engineering Weather Data is not only the standard for energy analysis within DOD, but also for the civilian sector (21:7.2).

Data for the determination of the designs' heating requirements was obtained from two sources. The sources are the energy computations from this study and Air Force Manual 88-29, Engineering Weather Data.

The necessary data for computing the differential initial investment costs was obtained from two sources. The sources are the designs accomplished in this study and Building Construction Cost Data 1981, which is updated yearly.

The results obtained from the performance of the four previous steps were then used as the basis of the life-cycle cost analyses. Guidance for accomplishing the life-cycle cost analysis was obtained from the Life-Cycle Costing Manual for the Federal Energy Management Programs. This manual was selected, because its use is dictated by the National Energy Conservation Policy Act of 1978, as ammended by Section 405 of the Energy Security Act (22:iii).

Model Development

This section develops the model used for estimating the differential initial investment costs for the different designs. To determine these costs required the identification of the components that change between the designs.

Passive solar design includes many energy conscious features, in addition to the techniques that admit sunlight through large sun-facing glass areas during the heating season. Most of the energy conscious features can be easily incorporated into a conventional design at little or no additional cost. However, the passive heating techniques that require heat storage cause significant changes in the exterior envelope of the structure and possibly in the size of the standard auxiliary heating system required for structure.

The exterior envelope of the structure is composed of the exterior walls, roof structure, foundation, and, in the case of a multiplex, any common wall. The costs that required determination, therefore, were the costs of the components that compose these sections of the structure and additionally the required auxiliary heating system.

Data Analysis Plan

Following the completion of the necessary designs, the energy requirements were computed for each design. As stated earlier, to determine the energy requirements required calculation of heat losses and any internal heat gains to the structure. Additionally, for the passive designs the amount of heat gained by the passive systems and delivered to the structure were computed to identify the structure's auxiliary heating requirements.

The "Patterns" method presented in The Passive Solar Energy Book, outlines a procedure for computing this needed information in an easy-to-follow step-by-step procedure and was determined to be one of the two best hand calculation methods currently available (2:72). This procedure does have one major omission. The method has no means for computing the heat gains obtained from lighting, equipment, or people. This situation was rectified by the addition of computational methods available in the Cooling and Heating Load Calculation Manual, as is the need for computation of any additional heat load required due to mandatory ventilation requirements.

For the example performed within this study, these losses and gains were omitted. In a residential environment these losses and gains are minimal and can be ignored, not so in office buildings, where these losses and gains can have a significant impact (21:7.6).

Following the computation of the energy requirements, the auxiliary heat load requirements were determined. Determination of these requirements was made using a variation of the "Patterns" method for determination of heat loss. This heat load equation is presented in Chapter IV.

Following the completion of the determination of auxiliary heat load requirements, the computation of the differential investment costs were accomplished. The quantity of each component of the systems identified earlier in this chapter was computed for each design. Prices for these components, which include the material, installation, and overhead and profit costs, were obtained from Building Construction Cost Data 1981. Using this data, the costs for each component were summed to obtain the total differential initial investment cost for each design.

Now that all the necessary inputs to the life-cycle analysis had been gathered, a life-cycle cost analysis was accomplished for each design. The actual equations used for this analysis, developed from guidance contained in Life-Cycle Costing Manual for the Federal Energy Management Programs, are contained in Appendix E.

As stated earlier, the escalation rates for energy prices change over three identified periods. Therefore, to develop the equations provided in Appendix E, required the identification of the base year, project start date, and length of the study period. This needed information is 1981, 1985, and 25 years, respectively (18:1).

Another concept incorporated into the life-cycle costing equations in Appendix E is the social value to the nation of conserving nonrenewable energy sources. This concept is incorporated by allowing a 10 percent reduction in investment costs for the structure. The 10 percent reduction is modeled after the 10 percent tax credit allowed to business for energy conservation and renewable energy investments (22:40).

After completion of the life-cycle cost analyses, the analyses were compared to identify the design with the least life-cycle cost. The identified design is this study's recommended design.

Scope

Due to the externally imposed constraint of time available for this research effort, the design and analysis of more than one configuration of a duplex unit was beyond the capability of the researcher. Therefore, this study was conducted using a three bedroom MFH duplex unit as the basis for design comparisons. This design should present results that can be generalized to the other MFH duplex units.

Similarly, since allowable square footages for MFH units vary depending on the category of the individual for which the unit is designed, the only unit that was designed and analyzed was for an enlisted occupant.

This design was selected because approximately 80 percent of the MX MFH units are planned for enlisted personnel (18:1).

Also due to the constraint of time, the designs and analyses can not be accomplished for every possible topography. Therefore, for the purposes of this study, the earth surrounding the structure was assumed to meet the foundation at some point below the exterior walls, yet above the foundation's footings.

Finally, as discussed earlier, five regions are currently being considered for siting the MX and its operational bases. The most probable sites of Beryl, Utah and Ely, Nevada were used as the sites for the purposes of the designs and analyses. These designs should be able to be generalized to the other sites if in fact the actual final locations are changed. This fact stems from the similarity of the climates of the five locations (17:12).

Assumptions

1. Heating degree-day requirements obtained from the M-X Renewable Energy Source Information Package for Cedar City, Utah were assumed to be representative for Beryl, Utah due to its relatively close proximity, approximately, thirty-four miles.

2. Due to the small cooling degree-day requirements for both sites, less than 10 percent of the heating degree-day requirements, and the similarities of the designs, cooling costs and loading requirements are assumed to be insignificant and were not computed.

3. Costs for building materials and their installation, including overhead and profit, were assumed to be representative of the average construction costs presented in Building Construction Cost Data 1981.

Limitations

1. Since data for Beryl, Utah is not available, Beryl's analyses are only as accurate as the degree to which Cedar City's climate approximates Beryl's.

2. Since the sites for the two operational bases are remote sites, and the requirements for building material during the construction of the bases will be great, material and installation costs in the local area will not be representative of the actual construction costs. Therefore, accurate cost data is not currently available to the researcher.

CHAPTER IV

DATA ANALYSIS

The purpose of this chapter is to present the analysis of data used in this economic feasibility study, which was used as an aid to develop the generalized procedure for such studies. The presentation of the data analysis followed the six basic steps identified in the methodology, which are: (1) accomplishment of the respective designs, (2) energy requirement computations, (3) auxiliary heat load requirement computations, (4) differential initial investment computations, (5) life-cycle analyses, and (6) comparison of the life-cycle cost results.

Accomplishment of the Respective Designs

Several requirements for the MFH unit structure are levied within Air Force Manual 88-25, Family Housing Design. These requirements include:

1. Minimum ceiling height of 7' - 8"

2. Maximum "U" factor
   a. ceiling - .05
   b. exterior wall - .10

3. Maximum of two baths for three bedroom unit

4. Maximum of combined exterior and interior storage of 85 and 50 square feet, respectively.

5. Maximum of 1080 square feet, which is calculated from:
   a. inside of walls (exterior)
   b. utility rooms, closets excluded
   c. bulk storage closets excluded

6. Duplex units for majors and below

7. Carport instead of garage for winter design temperatures greater than -10°F

8. Halls greater than 3 feet wide

9. Main bedroom must be able to accomodate 9 x 12 rug

10. Extra bedroom must be able to accomodate 8 x 10 rug.

ASHRAE Standard 90-75, Energy Conservation In New Building Design, was also reviewed for any requirements for "U" values. This standard allows "U" factors for the proposed sites of .24 for exterior walls and .076 for roofs and ceilings. These requirements are less stringent than the Air Force requirements. The more stringent requirements were used as the allowable limits for the designs.

In addition to the identified requirements, two other concepts were incorporated into the establishment of the common floor plan. These concepts are: (1) spaces in need of substantial heating and lighting requirements should be located on the south side of the structure, and (2) locate spaces having minimal heating and lighting requirements, such as cooridors and closets, along the north face of the structure (17:90). These concepts allow the spaces on the north side to serve as a buffer between the south side spaces and the colder north side (17:90). Figure 5 pictorially displays this concept.

Combining the aforementioned requirements and concepts established the floor plan used in this research. The resulting floor plan is displayed in Figure 6. The measurements shown within the figure generally apply to all

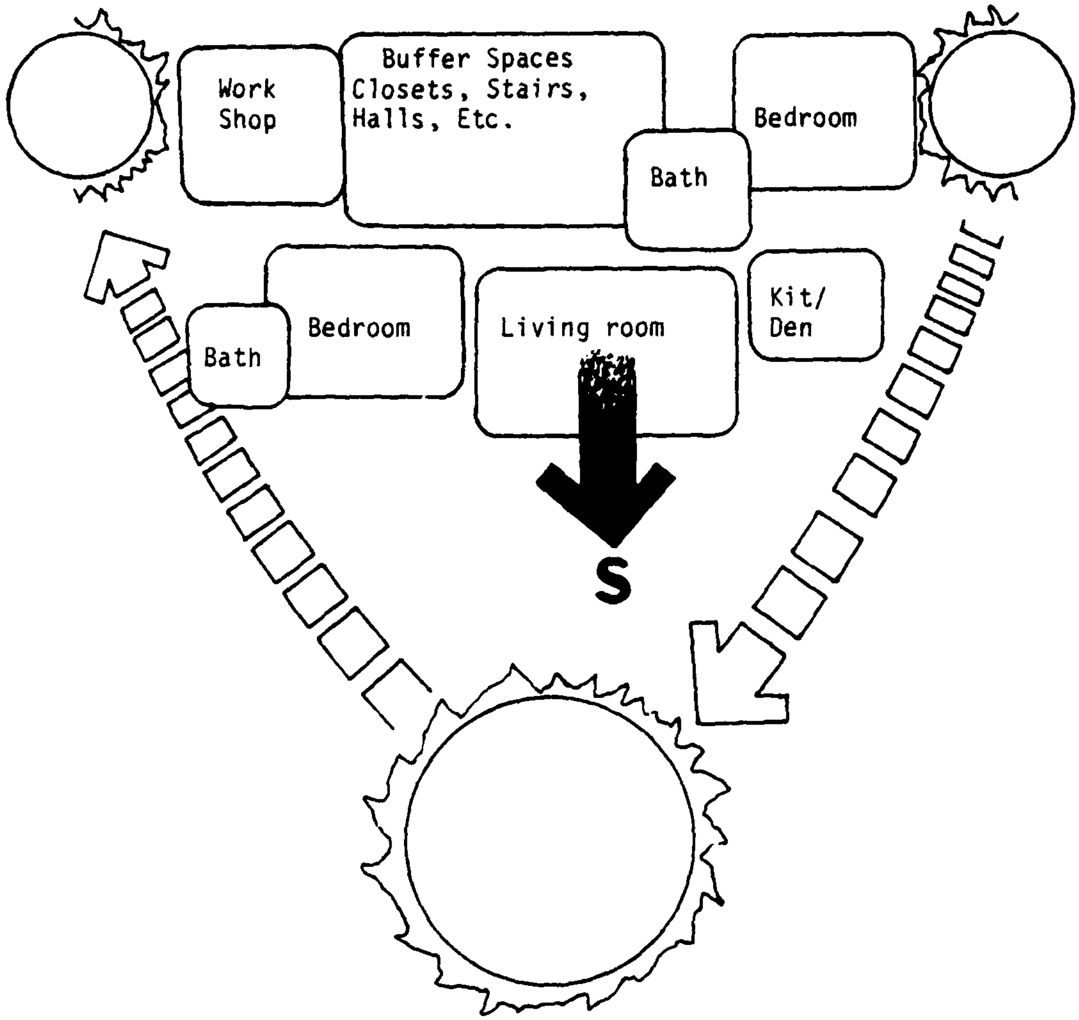


Fig. 5. Location of Indoor Spaces in Northern Hemisphere (17:91)

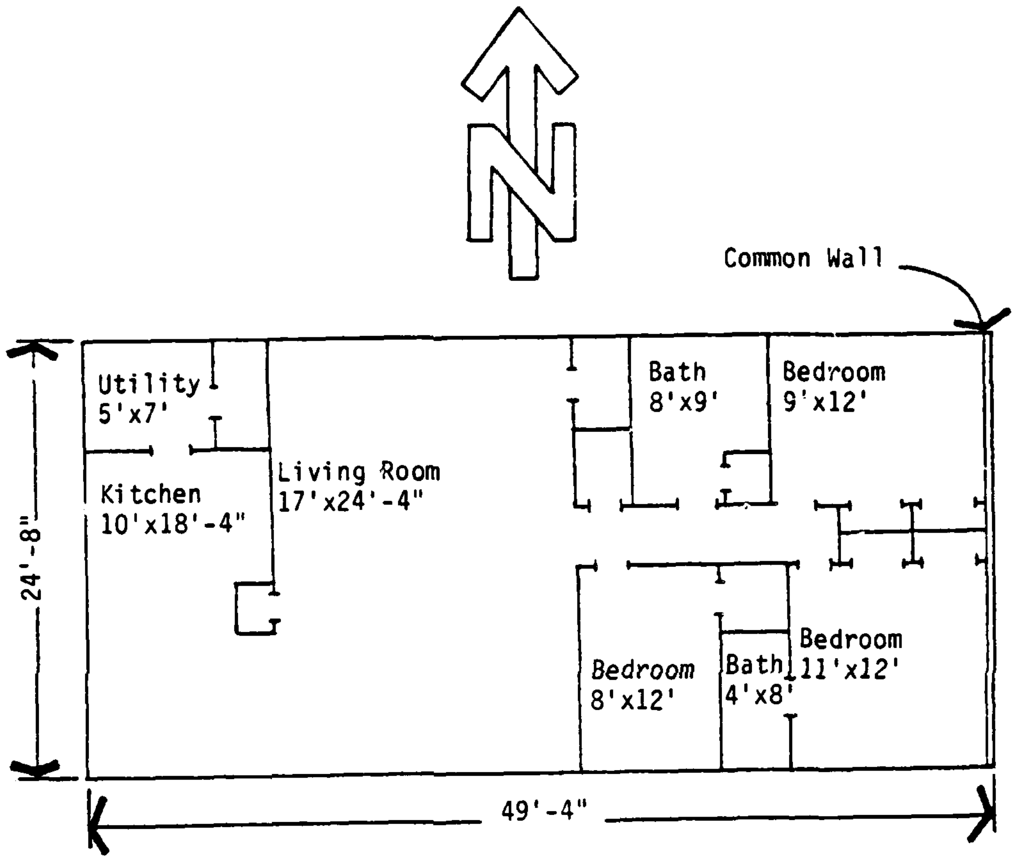


Fig. 6. Common Floor Plan

designs. Minor deviations on some measurements resulted from different interior finishes on the external walls. Additionally, the width of the structure was enlarged one foot in the combined system designs to accomodate the trombe wall.

Direct Gain Designs

To accomplish a direct gain design first required a determination of the amount of glass area required for the structure. The amount of glass area required was computed using Beryl, Utah's average January temperature of 29.1^{o}F and latitude of 37^{o} 42' NL (14:C-1). This data resulted in a ratio of .19 from Table 1 being used for determination of the required glass area. Multiplying this ratio by the 1250 square footage of the structure yielded a requirement of 237.5 or approximately 240 square feet of glass area. With this information and the previously formulated floor plan, the direct gain design for Beryl, Utah was accomplished. The detailed sections and southern elevation of this design are presented in Appendix B.

TABLE 1

SOLAR WINDOW SIZING (17:122)

Average Winter Outdoor Temperature (°F) (degree-days/mo.)[2]	Square Feet of Window Needed for Each One Sq Ft of Floor Area
Cold Climates	
15° (1500)	0.27-0.42 (w/night insul. over glass)
20° (1350)	0.24-0.38 (w/night insul. over glass)
25° (1200)	0.21-0.33
30° (1050)	0.19-0.29
Temperate Climates	
35° (900)	0.16-0.25
40° (750)	0.13-0.21
45° (600)	0.11-0.17

NOTES: 1. These ratios apply to a residence with a space heat loss of 8 to 10 BTU/day-sq ft floor -°F. If space heat loss is less, lower values can be used. These ratios can also be used for other building types having similar heating requirements. Adjustments should be made for additional heat gains from lights, people, and appliances.

2. Temperatures and degree-days are listed for December and January, usually the coldest months.

3. Within each range, choose a ratio according to your latitude. For southern latitudes, i.e., 35° NL, use the lower window-to-floor-area ratios; for northern latitudes, i.e., 48° NL, use the higher ratios.

For Ely, Nevada, with an average January temperature of 27.3°F and located at 39° 17' NL, Table 1 was entered at 25°F and due to Ely's relatively southern latitude the lower ratio of .21 was utilized for computational purposes (17:388). This ratio when multiplied by the 1250 square footage of the structure yielded a 262.5, or approximately 265 square footage, requirement for glass area. From this information the direct gain design for Ely, Nevada was accomplished. The detailed sections and southern elevation of this design are presented in Appendix B.

Combined System Designs

For the combined system designs no firm procedure has been established for determination of the optimum mix of direct and indirect gain components. For the purposes of this research, a trial and error approach was employed to determine the appropriate combination of direct and indirect gain components that resulted in an average temperature within the structure in January that was within a range of 70-75°F. This temperature range should provide sufficient comfort to the occupants.

For the Beryl, Utah combined system design this combination involved 204 square feet of direct gain glass area with an additional 199.5 square feet of glass area covering the trombe wall. This combination resulted in an average daily temperature in January of 72°F. The detailed sections and southern elevation of this design are presented in Appendix B.

For the Ely, Nevada combined system design, the combination involved 219 square feet of direct gain glass area with an additional 199.5 square feet of glass area covering the trombe wall. The detailed sections and southern elevation of this design are presented in Appendix B.

Conventional Designs

Due to the similar climatic conditions, average winter temperatures of 27.3 and 29.1^{o}F for Ely, Nevada and Beryl, Utah, respectively, the same conventional design was used for both sites. The conventional design was accomplished using the same floor plan as the other designs. Also, the design incorporated conventional construction materials, such as gypsum board to replace the brick thermal storage walls. In addition, an effort was made to keep the thermal resistance (U) of the exterior walls and roof structure, as close as practicable to the passive designs. The final U factors for the conventional structure's exterior walls and roof structure at values of .043 and .030 compare favorably with the .042 and .028 used in the passive designs.

The conventional design also incorporated sound energy conscious concepts. The incorporated concepts were minimization of the amount of north-facing glass, as well as minimizing the total glass area for the structure. The designs additionally ensure that the structure's glass area is shaded during the cooling season, but will still admit the sunlight during the heating season. The detailed sections and elevations of this design are presented in Appendix B.

Energy Requirement Computations

The necessary computations for heat losses, heat gains, and auxiliary heating requirements were computed for each passive design using the "Patterns" method (17:650). The computations for the conventional designs only entailed computation of heat losses and space heating requirements, but they were computed using the same "Patterns" method.

Accomplishment of the auxiliary heating requirements for the passive designs and the space heating requirements for the conventional designs yielded the information presented in Table 2. The detailed computations involved in the determination of these figures, are presented in Appendix C.

TABLE 2

ENERGY REQUIREMENTS

Type of Design	Location	Average Indoor Temp. (^{o}F)	Yearly Energy Requirements (MBTU)
Direct Gain	Beryl, Utah	65	34.1
Combined	Beryl, Utah	66	45.9
Conventional	Beryl, Utah	72	23.3
Direct Gain	Ely, Nevada	70	33.7
Combined	Ely, Nevada	--	38.9
Conventional	Ely, Nevada	--	49.5

Auxiliary Heat Load Requirement Computation

The sizing of the heating system was accomplished using the equation

$$Q = HL_{total}\ (T_i - T_o).$$

This equation is simply a variation of the "Patterns" method for determination of heat loss (17:560). In this equation: Q = design heat load requirement, HL_{total} = the hourly rate of heat loss for the entire space (obtained from

Appendix C), T_i = inside design temperature (68°F), and T_0 = outside design temperature, design dry-bulb 97.5 percent from Air Force Manual 88-29, <u>Engineering Weather Data</u>.

Table 3 presents the results of the auxiliary heat load requirement computations for Beryl, Utah and Table 4 presents the results for Ely, Nevada.

TABLE 3

BERYL, UTAH AUXILIARY HEAT LOAD REQUIREMENTS

Type of Design	HL_{total} (Btu/hr°F)	T_i (°F)	T_o (°F)	Q (Btu/hr)
Direct gain	408.1	68	5	25,710
Combined	435.9	68	5	27,462
Conventional	266.1	68	5	16,764

TABLE 4

ELY, NEVADA AUXILIARY HEAT LOAD REQUIREMENTS

Type of Design	HL_{total} (Btu/hr°F)	T_i (°F)	T_o (°F)	Q (Btu/hr)
Direct gain	423.8	68	-4	30,514
Combined	445.7	68	-4	32,090
Conventional	266.1	68	-4	19,159

Differential Initial Investment Computations

As developed earlier, the differential initial investment costs are confined to the exterior walls, roof structure, common wall, heating unit, and foundation. Each component of these units was costed according to prices in Building Construction Cost Data 1981. The results of this costing effort are presented in Table 5. The intermediate computations involved are presented in Appendix D.

TABLE 5

DIFFERENTIAL INITIAL INVESTMENT COSTS[3] (DIIC)

Type of Design	Location	DIIC ($)[1]	DIIC ($)[2]
Direct gain	Beryl, Utah	34,835.	35,105.
Combined	Beryl, Utah	38,860.	39,130.
Conventional	Beryl, Utah	24,260.	24,650.
Direct gain	Ely, Nevada	33,659.	33,929.
Combined	Ely, Nevada	38,885.	39,153.
Conventional	Ely, Nevada	24,380.	24,650.

NOTES: 1. Costs are based on electrical resistance heater.
2. Costs are based on natural gas furnace.
3. Baseline year is 1981.

Life-Cycle Cost Analyses

A life-cycle cost (LCC) analysis was performed for each design. The analyses used the 1981 cost data, which was reduced by 10 percent in accordance with the Life-Cycle Costing Manual for the Federal Energy Management Programs and then moved to the project start date of 1985. The transfer of these costs as dictated within the manual did not involve use of a discount rate.

The energy costs are based on 1981 prices and the respective escalation rates for mid-1980 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The energy costs were translated using standard engineering economy principles to the 1985 project start date. These energy costs were then summed with the investment costs to determine the life-cycle costs.

The results of these analyses are shown in Table 6. The detailed engineering economy equation used to compute the life-cycle costs is presented in Appendix E.

TABLE 6

RESULTS OF THE LIFE-CYCLE COST ANALYSES

Type of Design	Location	Life-Cycle Cost ($)[1]	Life-Cycle Cost ($)[2]
Direct gain	Beryl, Utah	36,823.	33,434.
Combined	Beryl, Utah	38,712.	36,474.
Conventional	Beryl, Utah	28,075.	24,282.

TABLE 6--Continued

Type of Design	Location	Life-Cycle Cost ($)[1]	Life-Cycle Cost ($)[2]
Direct gain	Ely, Nevada	40,711.	32,875.
Combined	Ely, Nevada	42,646.	36,955.
Conventional	Ely, Nevada	33,178.	24,707.

NOTES: 1. Costs are based on electrical resistance heating.
2. Costs are based on natural gas heating.

Comparison of Life-Cycle Cost Results

Comparison of the results of the life-cycle analyses indicated that within the limits imposed by the apriori assumptions, the conventional design resulted in the least life-cycle cost for both site locations. Review of the analyses indicated that this result is caused by the large investment costs associated with the mass required for thermal storage.

The availability of more accurate cost data for differential investment computations would probably change this study's computations somewhat. However, it is doubtful that any change would affect the overall result due to the degree of difference between the life-cycle costs.

The results of the sample study revealed that the change in heat load requirements between the various designs did not affect the size or cost of the heating system significantly. This situation is probably the result of the similarity of the designs and the common floor plan. Similar results can probably be expected for other design decisions as long as a common floor plan is used for all design alternatives. Therefore, the researcher believes the auxiliary heat load requirement computation can be eliminated from the generalized procedure. A complete discussion of all conclusions is presented in Chapter V.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

This research effort initially set out to develop a generalized procedure for Air Force planners to assess the feasibility of incorporating passive solar concepts into the design of new facilities versus using conventional construction. To develop this procedure the researcher reviewed the research efforts that had been accomplished in this area, as well as reviewing the requirements levied by the federal government.

The methodology adopted for this research effort was the determination of the factors needed for accomplishing a life-cycle cost analysis. The use of life-cycle cost analysis is required by Subpart A of Part 436 of Title 10 of the Code of Federal Regulations (22:iii). The researcher adapted the earlier research of Pumfrey and Thilgen for the civilian sector to include only the necessary components for a life-cycle cost analysis in the DOD environment. Additionally, the researcher performed an actual study to further clarify the factors needed for a generalized procedure.

Differential initial investment costs and energy costs were determined to be the necessary components for a life-cycle cost analysis in the DOD environment. The methodology used to determine these costs and whether or not the passive solar techniques should be included in a facility design involved a procedure comprised of six steps. The six steps are: (1) accomplishment of the respective designs, (2) energy requirement computation, (3) auxiliary heat load requirement computation, (4) differential initial investment cost computation, (5) life-cycle cost analyses computations, and (6) comparison of the life-cycle cost results. This methodology was applied to the design of the MX MFH units. The results revealed that for both Beryl, Utah and Ely, Nevada, conventional construction is preferable to the analyzed passive designs, because of its lower life-cycle costs.

Conclusions

The six step methodology used in this thesis with the exception of step three concerning auxiliary heating systems is a viable procedure for making passive solar/non-solar decisions. The method is not site specific and is complete to such a degree that it can be generalized to locations other than those under study. This assertion is based on the fact that all data used in the methodology are generally available to Air Force planners. The procedure needs only to be tempered by the twelve conclusions noted below in order to maintain consistent results among successive applications of the procedure.

1. Consistent U values for the various system sections comprising a facility's exterior envelope help ensure a meaningful comparison between alternative designs. For example, the roof structure U values should be as consistent as practicable between the alternative designs.

2. Establishment of a common floor plan for the alternative designs helps provide a meaningful basis of comparison. This floor plan incorporates any government guidance and additionally the location of indoor spaces concept presented in The Passive Solar Energy Book. The location of indoor

spaces concept locates areas requiring minimal heating and lighting along a facility's northern face to serve as a buffer between the heated spaces and the colder north face.

3. The mass required for thermal storage constitutes the major portion of the larger initial investment costs associated with the passive designs. Varying the composition of this wall may enhance the possibility of a passive design being economically feasible.

4. The "Patterns" method provides a basic framework for computing the energy requirements for alternative designs. This method does have a few minor omissions, however, these omissions are easily rectified.

5. The Cooling and Heating Load Calculation Manual presents in its Table 7.10A and 7.10B the information necessary for computing heat loss through below-grade walls, and basement floors, when earth berming is employed in the design of a facility.

6. Internal loads due to lighting and people are significant in large office type structures. The Cooling and Heating Load Calculation Manual in its Chapter 4 provides procedures for computation of these internal loads. For the alternative designs the required level of lighting can vary significantly due to the large amounts of glass area associated with passive designs. Therefore, for larger structures lighting loads should receive consideration and possibly computation. However, loads due to people or facility ventilation requirements are consistent between alternative designs and need not be computed.

7. The "Patterns" method does not adequately describe how to derive the Solar Heating Fraction (SHF). The monthly unshaded glass area and solar energy absorbed computations necessary to derive the appropriate SHF can be

accomplished using the data available in Table 3.29 of the Cooling and Heating Load Calculation Manual. This data can then be used to make the necessary computations, as shown in the sample in Appendix C of this study.

8. Computation of the auxiliary heat loads for the alternative designs is unnecessary. The MX MFH unit example performed in this study revealed only nonexistent or insignificant changes in cost for the heating systems of the alternative designs.

9. The components comprising the various sub-systems of the facility's exterior envelope provide the necessary inputs for determining the differential initial investment costs for each alternative design.

10. The Life-Cycle Costing Manual for the Federal Energy Management Programs provides a basic framework for performing life-cycle cost analyses relating to new facility design and retrofit projects. However, this manual does have one major shortcoming. That shortcoming is that all prices are tied to 1980 dollars. This situation is not a significant problem for a 1981 baseline year, but as the baseline year falls further out in the future, this source of error does become significant. Current information in the manual indicates that this situation is rectified periodically with the publication of new energy prices in the Federal Register (22:137).

11. The equation used in this study to compute life-cycle costs can be used for other design decisions unless the planner can identify a change in maintenance costs between the alternative designs. If the maintenance costs can be shown to change, maintenance costs should be added to the life-cycle cost equation and discounted at 7 percent.

12. The equation used in this study to compute energy costs is valid only for projects with a 1981 baseline year, a 1985 project start, and a 25 year life for the facility. However, the proper equation for any

design decision can be determined by basing all necessary costs on the baseline year. The established differential initial investment costs are then moved to the project start with no adjustment. All other costs are translated to the project start at the appropriate discount rate, using standard engineering economy principles.

Recommendations

The researcher recommends that the information contained in the above generalized procedure be provided in handbook form to Air Force planners tasked with the design of facilities. Such a handbook will help Air Force planners comply with existing law requiring the consideration of solar technology in facility design.

Recommendation for Further Research

During this research effort the author encountered a new passive concept. This concept is the so-called double-shell design of architect Lee Porter Butler. If the design operates as Butler contends, the facility requires no backup heating or cooling system. Elimination of these systems and their associated energy usage should offset any additional initial investment costs required for constructing the double-shell design. The researcher recommends that this concept be studied to determine, if in fact the system operates as Butler contends. If this system should prove its merit, the concept could be of great value to not only the Air Force and Department of Defense, but also to the entire country.

APPENDICES

APPENDIX A

ABBREVIATIONS AND VARIABLES

Below is a listing of the abbreviations and variables used frequently within this thesis. This appendix establishes the definition of these abbreviations and variables.

A	--Area
A_{floor}	--Floor area
A_{gl}	--Unshaded glass area for any month within the year
Btu	--British Thermal Unit
Conversion factor	--Horizontal to vertical conversion factor for average solar radiation from the graph on page 384 of The Passive Solar Energy Book.
CY	--Cubic yard
DD_{mo}	--Degree days ^{o}F for a month
Ea	--Each
E_c	--Energy price for the baseline year
e	--Escalation rate from Table C-6
e_c	--Energy used yearly in MBtu
e_2	--Escalation rate for mid-1985 to mid-1990 (Table C-7)
e_3	--Escalation rate for mid-1990 to mid-1995 and beyond (Table C-8)
F	--Edge loss factor from Table V-3 in The Passive Solar Energy Book
FBM	--Feet Board Measure
Gal	--Gallon
HG	--Heat Gain

HG_{sol} --Direct Solar Heat Gain

HG_{sp} --Space Heat Gain

HG_{tm} --Trombe Wall Heat Gain

HL --Heat Loss

HL_{total} --Space Heat Loss

I_{costs} --Differential initial investment costs

I_t --Solar heat gain through one square foot of glazing in Btu/day available from Input Data for Solar Systems or The Passive Solar Energy Book, Appendix I.

I_{tc} --I_t for a day in the coldest month of the year

LF --Linear Feet

MBtu --Million Btus

N --Number of periods to be discounted

N_u --Number of windows

n --Number of air changes per hour from Table V-4 in The Passive Solar Energy Book.

n_{ps} --Number of years from feasibility study to the project start.

P --Perimeter length of floor slab edge in feet (17:651).

P_r --Horizontal distance from exterior wall to roof edge in feet (same as P in the Cooling and Heating Load Calculation Manual)

Q --Standard auxiliary heat load requirements

Q_{aux} --Auxiliary Space Heating Requirement in Btus

$Q_{aux\ year}$ --Yearly Auxiliary Space Heating Requirement in Btus

Q_c month --Monthly Solar Heating Contribution for Direct Gain Systems, Thermal Storage Walls, and Roof Ponds in Btus.

Q_r month --Monthly Space Heating Requirement in Btus.

Q_r year --Yearly Space Heating Requirement in Btus.

R --Thermal resistance in Hr ^{o}F/Btu

RES --Renewable Energy Sources

S_A --Surface absorption obtained from The Passive Solar Energy Book.

SF --Square feet

SH --Shadow length vertically for roof projection

SH/P_r --Shadow length, foot per foot of roof projection from Table 3.29 in Cooling and Heating Load Calculation Manual, which uses the term SH/P.

SQ --One hundred square feet

SY --Square yard

t_i --Daily average indoor temperature

t_o --Average daily outdoor temperature available from Air Force Manual 88-29 Engineering Weather Data of Appendix G of The Passive Solar Energy Book.

T_i --Inside design temperature

T_o --Outside design temperature

U --Heat transfer coefficient in Btu/hr SF ^{o}F

U_{sp} --Rate of space heat loss per square foot of floor area

V --Volume of the space in cubic feet

Ve --Vertical distance from roof edge to bottom of glass area

APPENDIX B

DETAILS OF THE ALTERNATIVE DESIGNS

U Value Computation for the Passive Designs' South and West Exterior Walls and All Exterior Walls of the Conventional Design

COMPONENT	R VALUE[1]
Outside air	.17
1" Stucco	.20
3/4" Plywood	.93
3/4" Fiber board	2.06
3-1/2" Polystyrene insulation	18.41
5/8" Gypsum board	.56
Inside air	.68
Total Exterior Wall R Value =	23.01

$U = 1/R = 1/23.01 = .043$

NOTE: 1. R values obtained from Table 3.1A in the Cooling and Heating Load Calculation Manual.

U Value Computation for the Passive Designs' North Thermal Storage Wall

COMPONENT	R VALUE[1]
Outside air	.17
1" Stucco	.20
3/4" Plywood	.93
3/4" Fiber board	2.06
3-1/2" Polystyrene insulation	18.41
4" Common brick	.80
4" Face brick	.44
Inside air	.68

Total North Thermal Storage Wall R Value = 23.69

U = 1/R = 1/23.69 = .042

NOTE: 1. R values obtained from Table 3.1A in the Cooling and Heating Load Calculation Manual.

U Value Computation for the Combined Systems' Trombe Wall

COMPONENT	R VALUE[1]
Outside air	.17
Double glazing	2.04
4" Air space	1.01
14" Common brick	2.80
Inside air	.61

Total Trombe Wall R Value = 6.63

$U = 1/R = 1/6.63 = .15$

NOTE: 1. R values obtained from Table 3.1A in the Cooling and Heating Load Calculation Manual.

U Value Computation for the Roof of the Passive Designs

COMPONENT	R VALUE[1]
Outside air	.17
Asphalt shingles	.44
3/4" Plywood	.93
1" Air space	1.87
8-1/2" Fibrous glass insulation with foil face	30.00
3/4" Air space	1.10
1/2" Gypsum board	.45
Inside air	.61

Total Roof R Value = 35.57

$$U = 1/R = 1/35.57 = .028$$

NOTE: 1. R values obtained from Table 3.1A in the Cooling and Heating Load Calculation Manual.

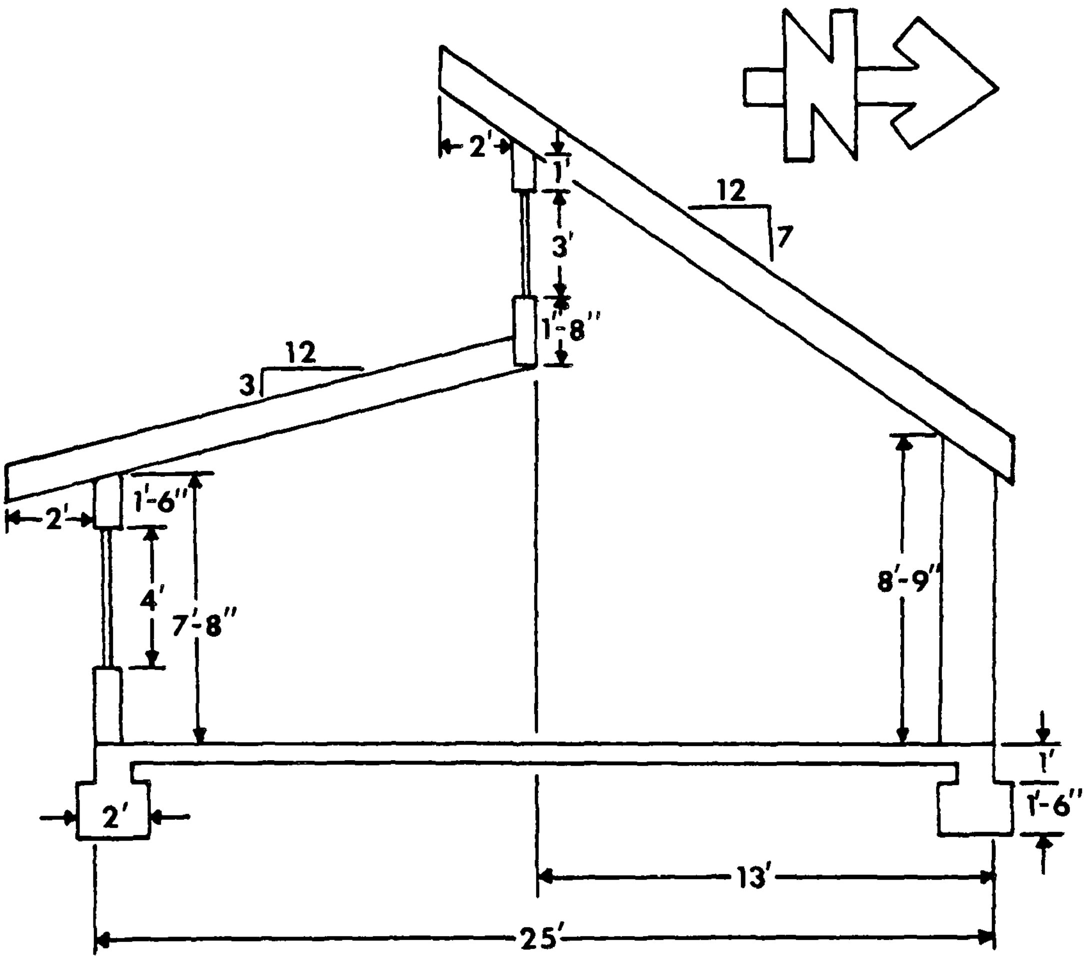
U Value Computation for the Roof of the Conventional Design

COMPONENT	R VALUE[1]
Outside air	.17
Asphalt shingles	.44
3/4" Plywood	.93
Dead air space	.93
8-1/2" Fibrous glass insulation with foil face	30.00
1/2" Gypsum board	.45
Inside air	.61

Total Roof R Value = 33.53

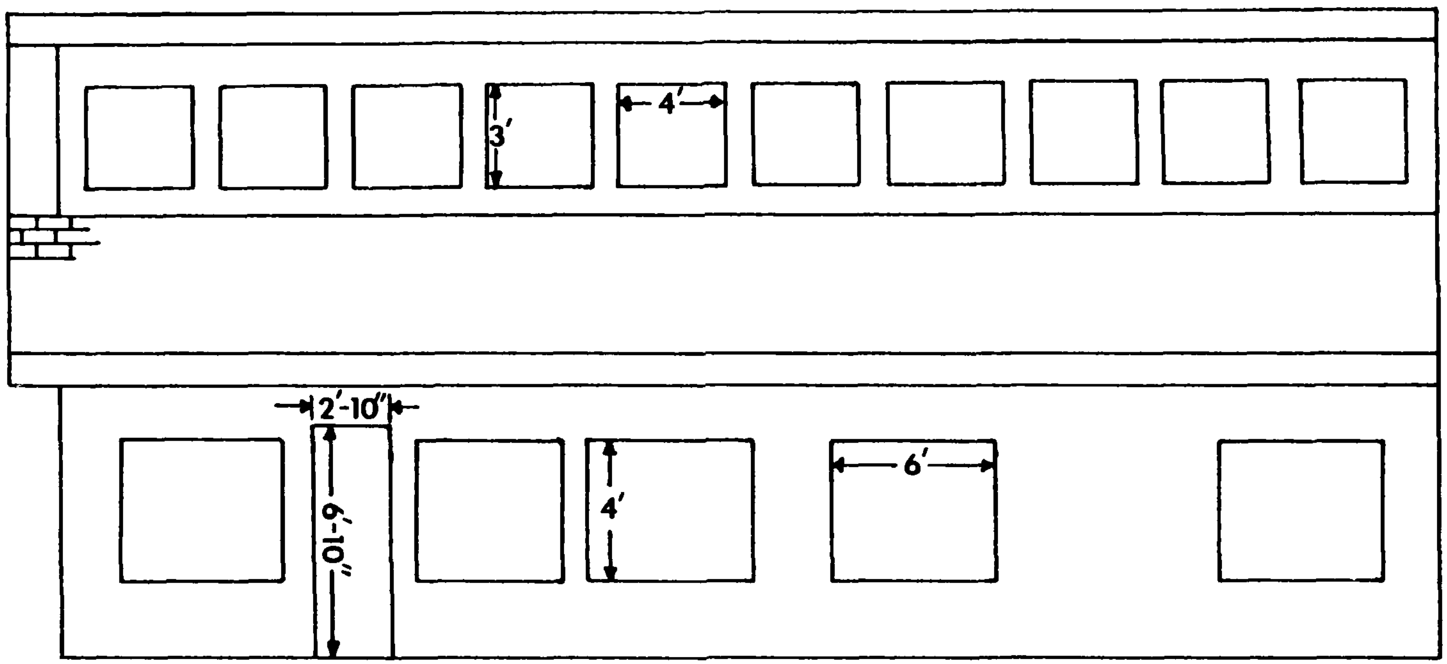
$U = 1/R = 1/33.53 = .030$

NOTE: 1. R values obtained from Table 3.1A in the Cooling and Heating Load Calculation Manual.

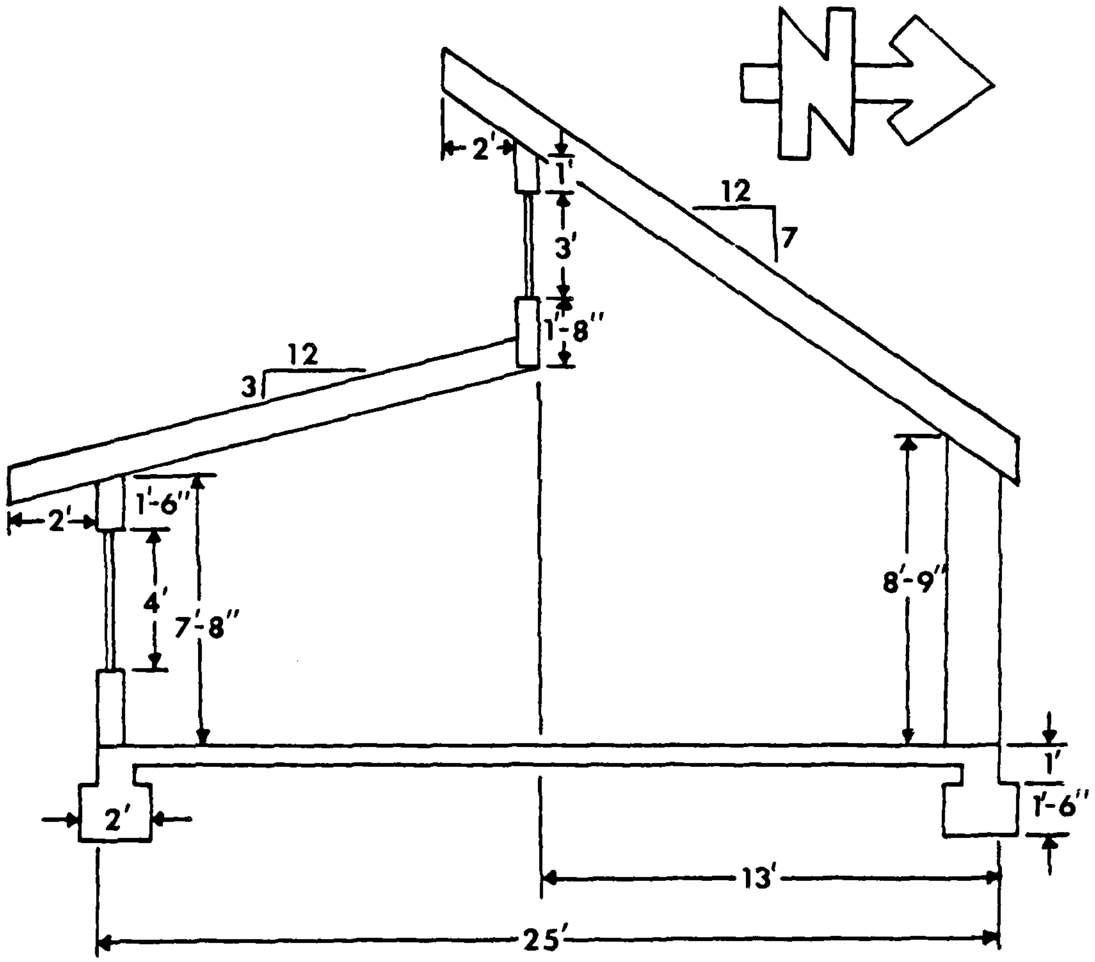


Side View Section of Direct Gain

Design for Beryl, Utah

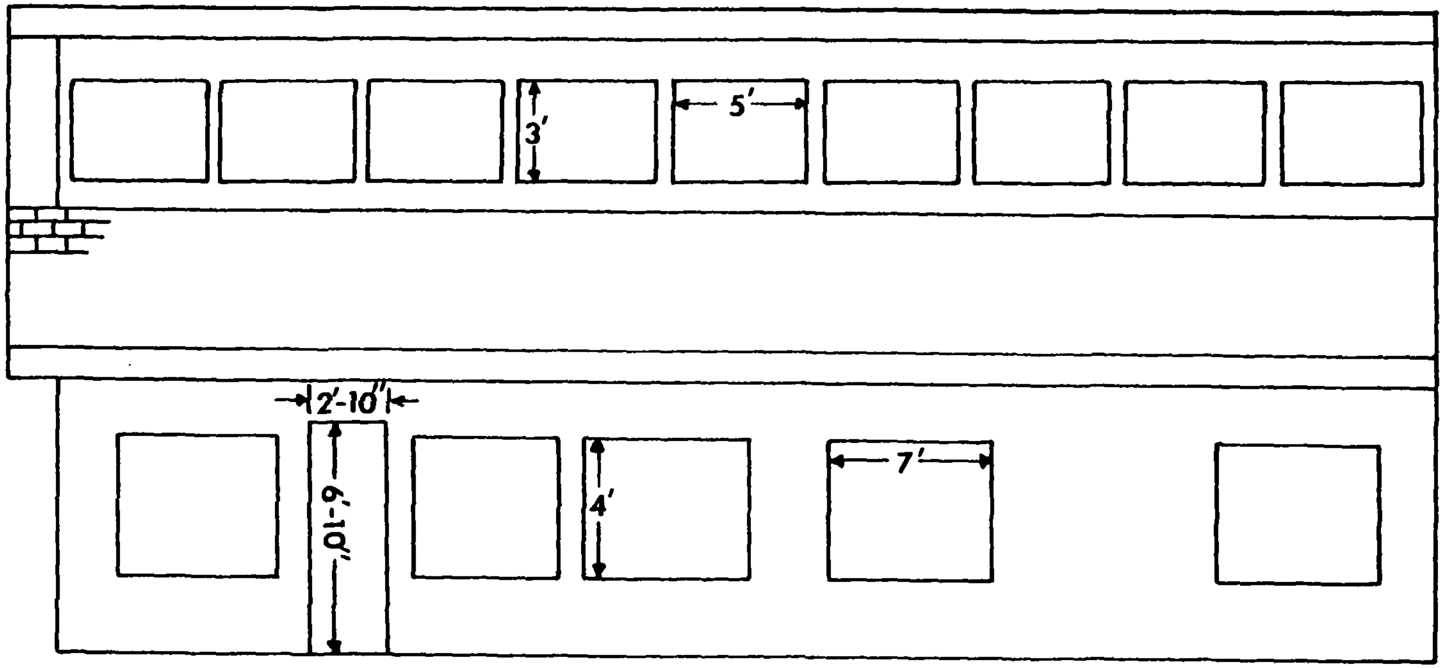


South Elevation of Direct Gain Design at Beryl, Utah

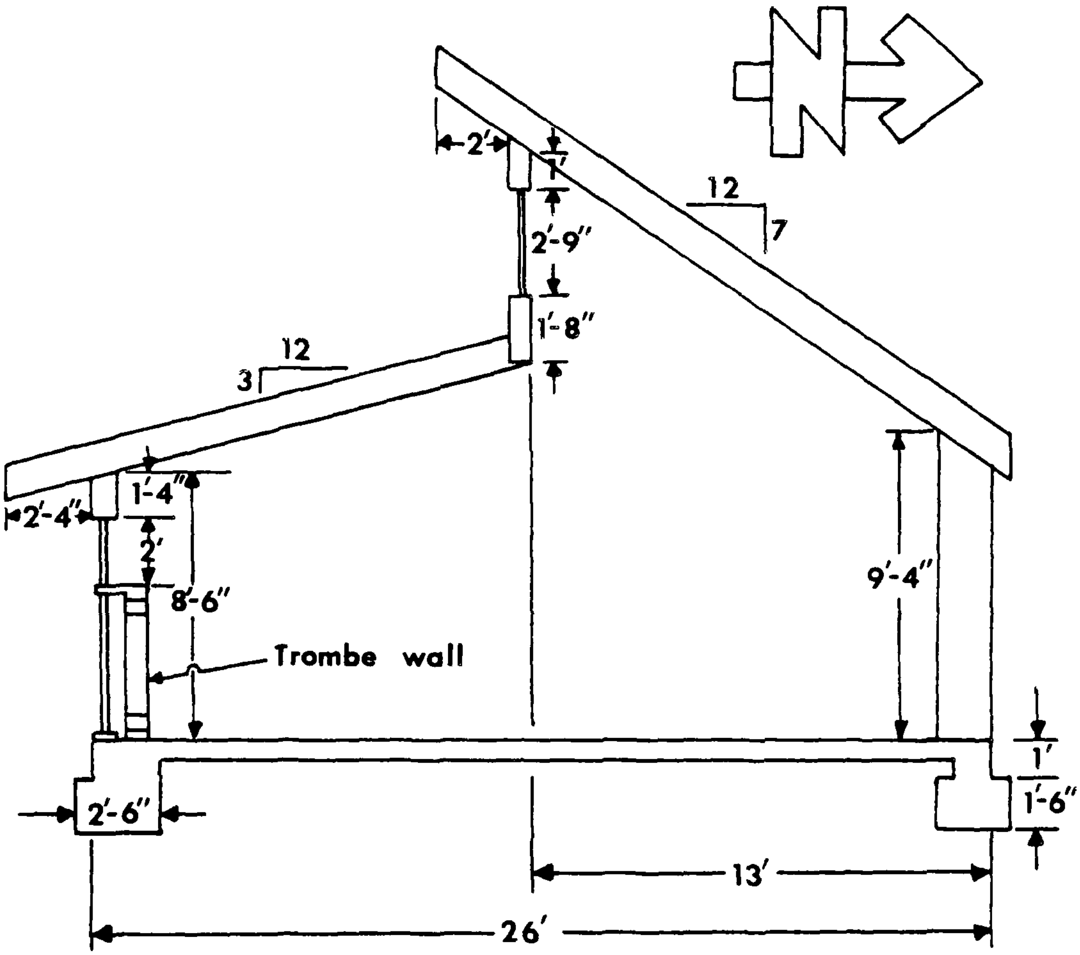


Side View Section of Direct Gain

Design for Ely, Nevada

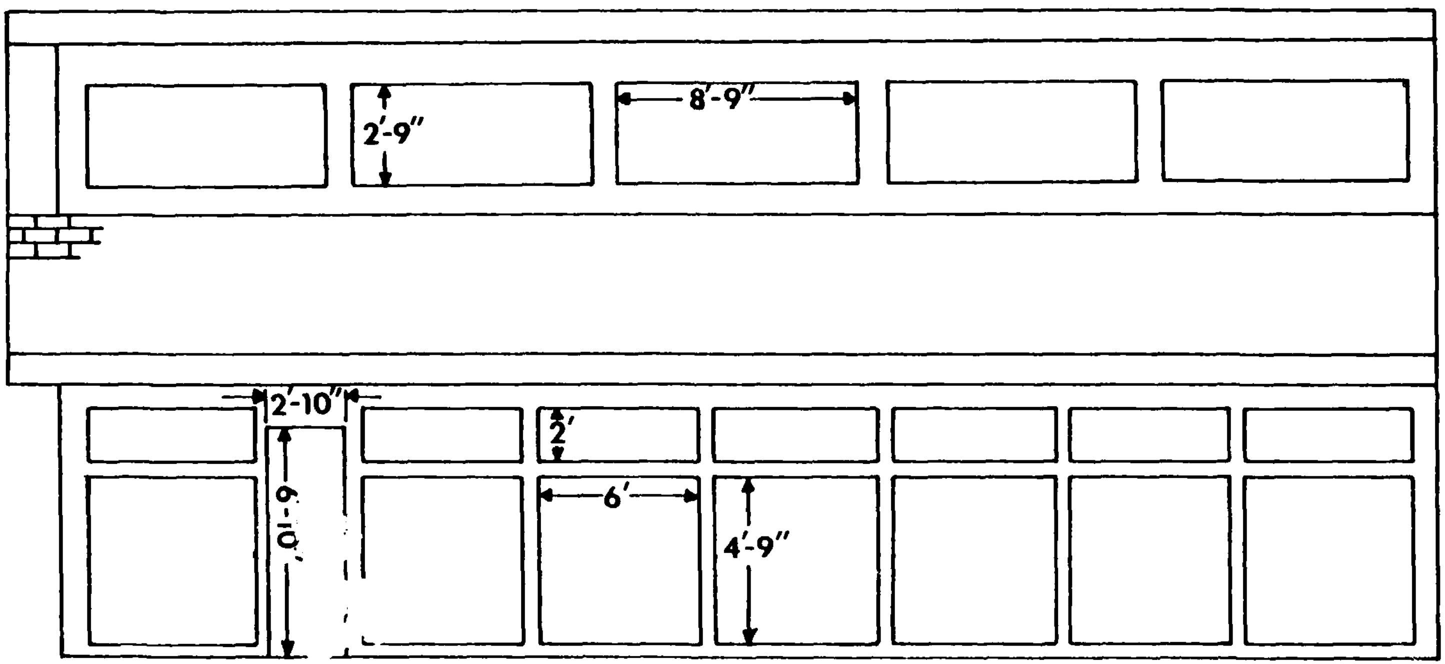


South Elevation of Direct Gain Design at Ely, Nevada

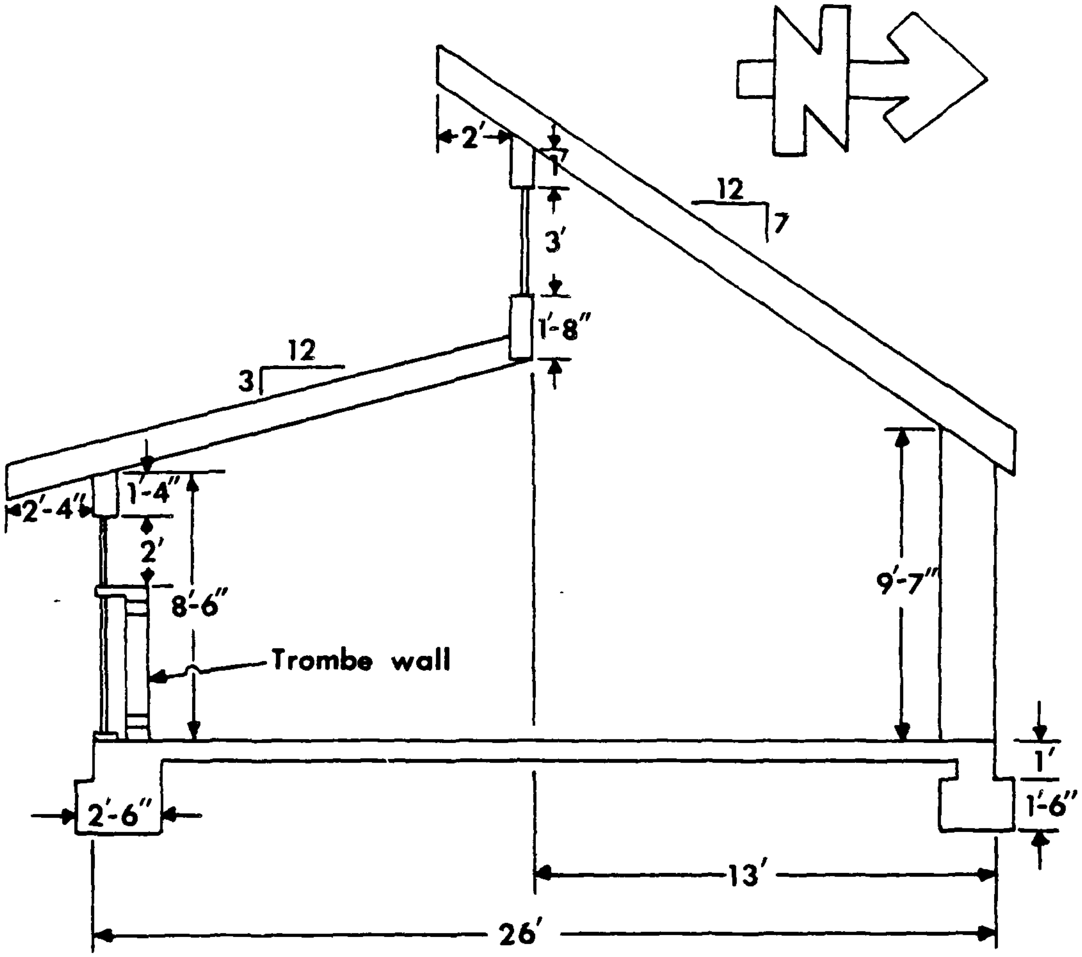


Side View Section of Combined System

Design for Beryl, Utah

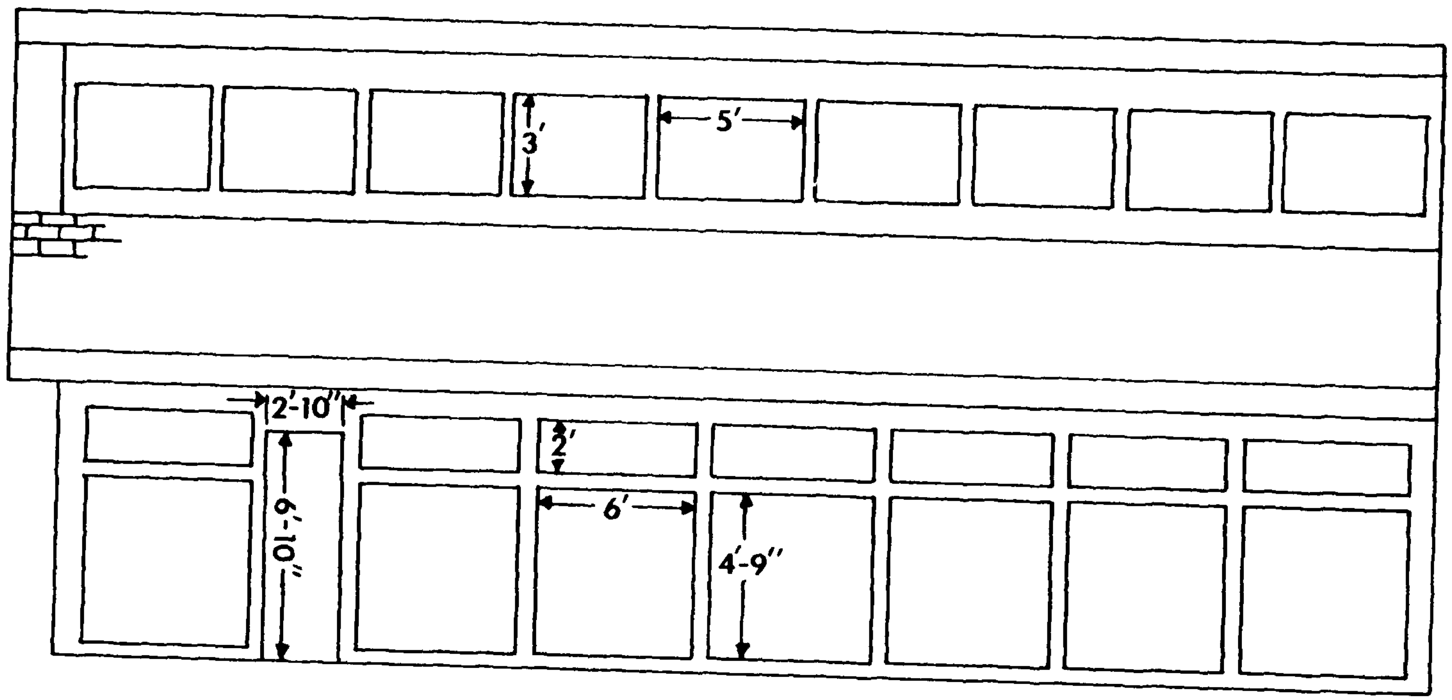


South Elevation of Combined System Design at Beryl, Utah

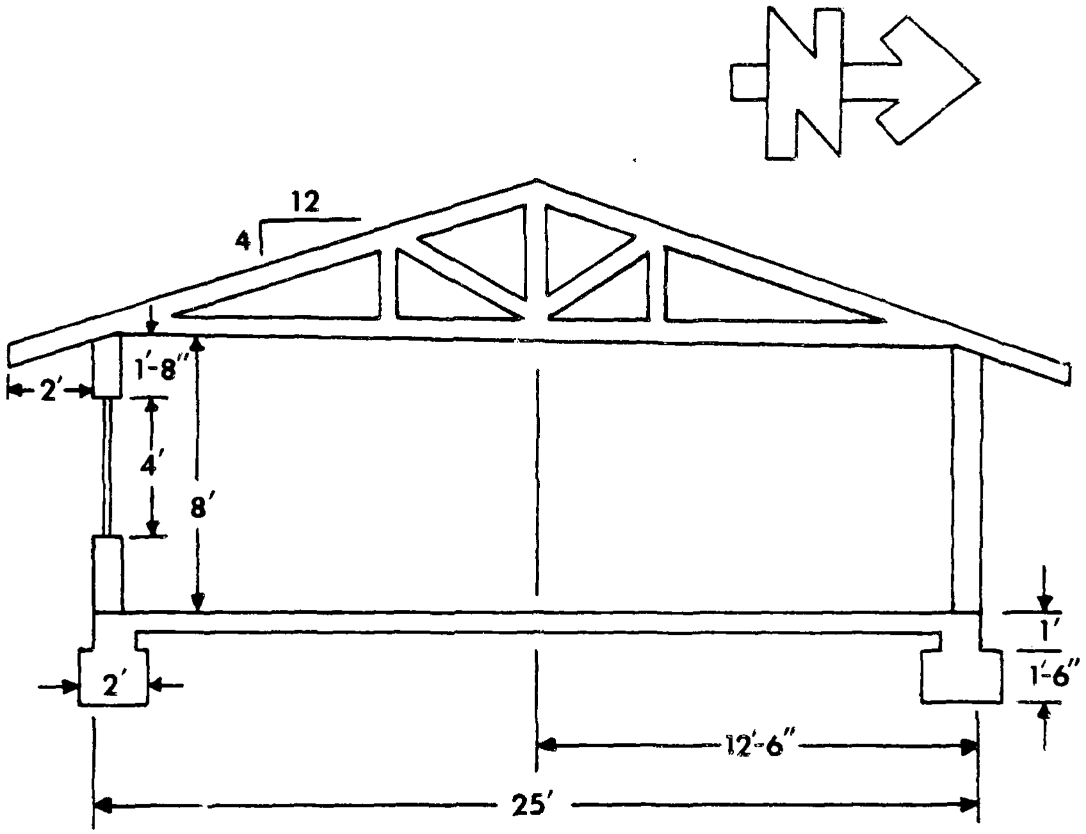


Side View Section of Combined System

Design for Ely, Nevada

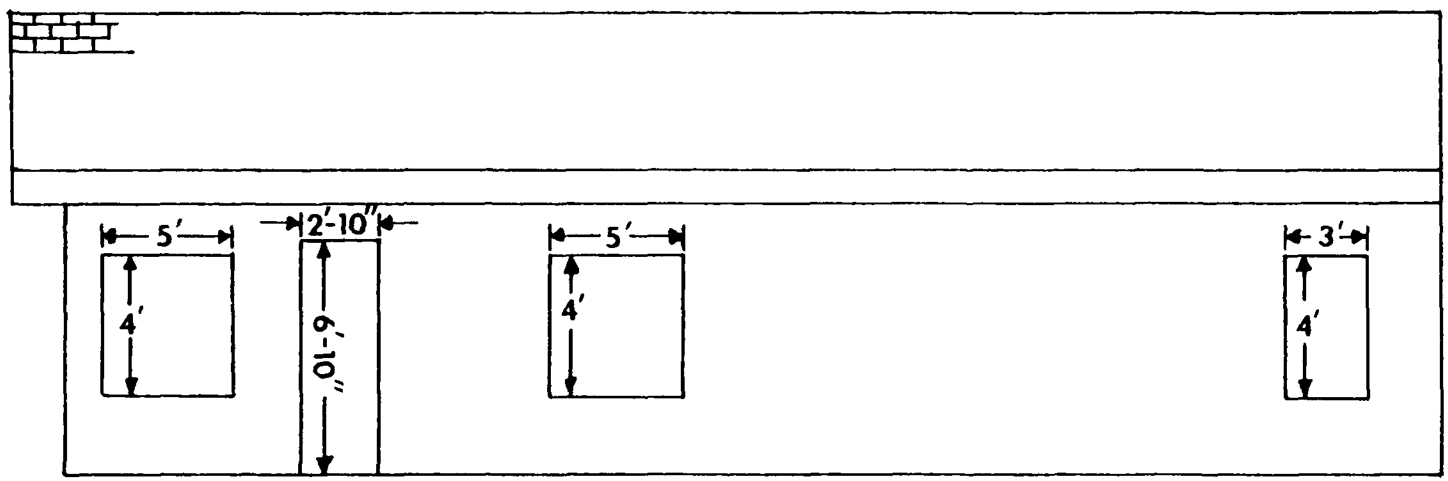


South Elevation of Combined System Design at Ely, Nevada



Side View Section of Conventional Design

for Beryl, Utah and Ely, Nevada



South Elevation of the Conventional Design

at Beryl, Utah and Ely, Nevada

APPENDIX C

ENERGY COMPUTATIONS

This appendix presents the detailed energy computations involved in the determination of yearly energy requirements for each design. The computations are presented on the standard forms available in Appendix M of The Passive Solar Energy Book. Additionally, a sample computation is shown for the calculations necessary to determine the monthly Solar Heating Fractions (SHF). The SHF is the fraction of the monthly space heating load that is supplied by solar energy (17:653). The sample shown is for the direct gain design at Beryl, Utah.

Preliminary calculations for determination of monthly SHF.

Lower windows:

December 12 noon $SH/P_r = .5$

$SH = (SH/P_r) = .5 \times 2 = 1.0$ foot

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 1) \times 6 \times 5 = 120$ SF

January/November 12 noon $SH/P_r = .6$

$SH = (SH/P_r) = .6 \times 2 = 1.2$ feet

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 1.2) \times 6 \times 5 = 114$ SF

February/October 12 noon $SH/P_r = .8$

$SH = (SH/P_r) \times P_r = .8 \times 2 = 1.6$ feet

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 1.6) \times 6 \times 5 = 102$ SF

March/September 12 noon $SH/P_r = 1.2$

$SH = (SH/P_r) = 1.2 \times 2 = 2.4$ feet

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 2.4) \times 6 \times 5 = 78$ SF

April/August 12 noon $SH/P_r = 1.9$

$SH = (SH/P_r) = 1.9 \times 2 = 3.8$ feet

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 3.8) \times 6 \times 5 = 36$ SF

May/July 12 noon $SH/P_r = 2.7$

$SH = (SH/P_r) = 2.7 \times 2 = 5.4$ feet - greater than 5 feet

$A_{gl} = 0$

June 12 noon $SH/P_r = 3.3$

$SH = (SH/P_r) = 3.3 \times 2 = 6.6$ feet - greater than 5 feet

$A_{gl} = 0$

Clerestory windows:

December 12 noon $SH/P_r = .5$

$SH = (SH/P_r) \times P_r = .5 \times 2 = 1.0$ foot - less than 2 feet

$A_{gl} = 3 \times 4 \times 10 = 120$ SF

January/November 12 noon $SH/P_r = .6$

$SH = (SH/P_r) \times P_r = .6 \times 2 = 1.2$ feet - less than 2 feet

$A_{gl} = 3 \times 4 \times 10 = 120$ SF

February/October 12 noon $SH/P_r = .8$

$SH = (SH/P_r) \times P_r = .8 \times 2 = 1.6$ feet - less than 2 feet

$A_{gl} = 3 \times 4 \times 10 = 120$ SF

March/September 12 noon $SH/P_r = 1.2$

$SH = (SH/P_r) \times P_r = 1.2 \times 2 = 2.4$ feet

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 2.4) \times 4 \times 10 = 104$ SF

April/August 12 noon $SH/P_r = 1.9$

$SH = (SH/P_r) \times P_r = 1.9 \times 2 = 3.8$ feet

$A_{gl} = (V_e - SH) \times W_w \times N_u = (5 - 3.8) \times 4 \times 10 = 48$ SF

May/July 12 noon $SH/P_r = 2.7$

$SH = (SH/P_r) \times P_r = 2.7 \times 2 = 5.4$ feet - greater than 5 feet

$A_{gl} = 0$

June 12 noon $SH/P_r = 3.3$

$SH = (SH/P_r) \times P_r = 3.3 \times 2 = 6.6$ feet - greater than 5 feet

$A_{gl} = 0$

Monthly solar energy absorbed is determined by the equation:

$A_{gl} \times I_t \times$ Conversion factor $\times S_A \times$ Number of days in the month

January	= (114 + 120)(871.6 x 1.17)(.90)(31)	=	6,657,683 Btu
February	= (102 + 120)(1255 x .93)(.90)(28)	=	6,529,504
March	= (78 + 104)(1749.8 x .63)(.90)(31)	=	5,597,635
April	= (36 + 48)(2103.3 x .41)(.90)(30)	=	1,955,817
May	= (0 + 0)	=	0
June	= (0 + 0)	=	0
July	= (0 + 0)	=	0

August = (86 + 48)(2307.7 x .34)(.90)(31) = 1,838,831

September = (78 + 104)(1935 x .52)(.90)(30) = 4,944,467

October = (102 + 120)(1473 x .79)(.90)(31) = 7,207,539

November = (114 + 120)(1078.6 x 1.08)(.90)(30) = 7,359,762

December = (120 + 120)(814.8 x 1.22)(.90)(31) = 6,656,199

Monthly Solar Load Ratio (SLR) is determined by the following equation, which is used to determine the month's SHF:

$$SLR = \frac{\text{monthly solar energy absorbed}}{Q_r\text{month}}$$

$$\text{Jan} = \frac{6,657,683}{11,025,000} = .60 \qquad \text{Jul} = \frac{0}{0} = 0$$

$$\text{Feb} = \frac{6,529,504}{8,751,400} = .75 \qquad \text{Aug} = \frac{1,838,831}{58,800} = 31.3$$

$$\text{Mar} = \frac{5,597,635}{8,085,000} = .69 \qquad \text{Sep} = \frac{4,944,467}{1,117,200} = 4.43$$

$$\text{Apr} = \frac{1,955,817}{5,262,600} = .37 \qquad \text{Oct} = \frac{7,207,539}{4,155,200} = 1.73$$

$$\text{May} = \frac{0}{2,753,800} = 0 \qquad \text{Nov} = \frac{7,359,762}{7,702,800} = .96$$

$$\text{Jun} = \frac{0}{838,000} = 0 \qquad \text{Dec} = \frac{6,656,199}{10,388,000} = .64$$

Direct gain - Beryl, Utah

Step 1. Calculating Space Heat Loss

a. Heat Loss Calculations

Item	A	x	U		=	Btu/hr-°F
Exposed wall	406.2	x	.042		=	17.1
Exposed wall	674.8	x	.043		=	29.0
Exposed wall		x			=	
Roof	1371	x	.028		=	38.4
Door (exterior)	38.6	x	.33		=	12.7
Exposed glass	258	x	.49		=	126.4
Floor slab edge	P 125	x	F .17		=	21.3
Infiltration	V 13,655	x	n .67	x 0.018	=	163.9
				HL_{total}	= 408.8	Btu/hr-°F

where: A = exposed wall, floor, roof, door and glass area in square feet
U = overall coefficient of heat transmission in Btu/hr-sq ft-°F
P = perimeter length of floor slab edge in feet
F = edge loss factor from table V-3 in chapter 5
V = volume of the space in cubic feet
n = number of air changes per hour from table V-4 in chapter 5

b. Calculating the Rate of Space Heat Loss per Square Foot of Floor Area (U_{sp})

$$U_{sp} = \frac{HL_{total}}{A_{floor}} \times 24 \text{ hours} = \text{Btu/day-sq ft}_{floor}\text{-°F}$$

where: A_{floor} = floor area in square feet

$$U_{sp} = \frac{408.8}{1250} \times 24 = 7.84$$

Step 2. Calculating Space Heat Gain

a. *Direct Solar Heat Gain*

Item		A_{gl}	x	I_t	=	Btu/day
Glass area	South	240	x	1457	=	349,680
	SE, SW		x		=	
	East, West		x		=	
	NE, NW		x		=	
	North		x		=	
				HG_{sol}	=	349,680 Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet

I_t = solar heat gain through one square foot of glazing in Btu/day

b. *Heat Gain from a Thermal Storage Wall, Roof Pond or Attached Greenhouse*

Item	A_{gl}	x	I_t	x	P	=	HG_{tm}	Btu/day
Collector area		x		x		=		Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet

I_t = solar heat gain through one square foot of glazing in Btu/day

P = percentage of incident energy on the face of a thermal wall or roof pond that is transferred to the space from figure V-6 in chapter 5

c. *Calculating Space Heat Gain per Square Foot of Floor Area*

$$HG_{sp} = \frac{HG_{sol}}{A_{floor}} + \frac{HG_{tm}}{A_{floor}} = \text{Btu/day-sq ft}_{floor}$$

where: A_{floor} = floor area in square feet

$$HG_{sp} = \frac{349{,}680}{1250} + 0 = 279.7$$

Step 3. Determining Average Indoor Temperature

$$\text{daily average indoor temperature } (t_i) = \frac{HG_{sp}}{U_{sp}} + t_o$$

where: HG_{sp} = rate of space heat gain in Btu/day-sq ft_{floor}
U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
t_o = average daily outdoor temperature from Appendix G

$$t_i = \frac{279.9}{7.84} + 29.1 = 64.8^{\circ}F$$

Step 4. Determining Daily Space Temperature Fluctuations

See chapter 5, Fine Tuning

Step 5. Calculating Auxiliary Space Heating Requirements

a. *Space Heating Requirements (Q_r)*

	U_{sp}	x	A_{floor}	x	DD_{mo}	=	$Q_{r\ month}$ (Btu's)
January	7.84	x	1250	x	1125	=	11,025,000
February	7.84	x	1250	x	893	=	8,751,400
March	7.84	x	1250	x	825	=	8,085,000
April	7.84	x	1250	x	537	=	5,262,600
May	7.84	x	1250	x	281	=	2,753,800
June	7.84	x	1250	x	85	=	833,000
July	7.84	x	1250	x	0	=	0
August	7.84	x	1250	x	6	=	58,800
September	7.84	x	1250	x	114	=	1,117,200
October	7.84	x	1250	x	424	=	4,155,200
November	7.84	x	1250	x	786	=	7,702,800
December	7.84	x	1250	x	1060	=	10,388,000
					$Q_{r\ year}$	=	60,132,800 (Btu/year)

where: U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
A_{floor} = floor area in square feet
DD_{mo} = degree-days per month

b. *Solar Heating Contribution for Direct Gain Systems, Thermal Storage Walls and Roof Ponds* (Q_c)

	$Q_{r\ month}$	x	solar heating fraction (SHF)	=	$Q_{c\ month}$ (Btu's)	
January	11,025,000	x	.37	=	4,079,250	
February	8,751,400	x	.46	=	4,025,644	
March	8,085,000	x	.44	=	3,557,400	
April	5,262,600	x	.23	=	1,210,398	
May	2,753,800	x	0	=	0	
June	833,000	x	0	=	0	
July	0	x	0	=	0	
August	58,800	x	1.00	=	58,800	
September	1,117,200	x	1.00	=	1,117,200	
October	4,155,200	x	.82	=	3,407,264	
November	7,702,800	x	.57	=	4,390,596	
December	10,388,000	x	.40	=	4,155,200	
			$Q_{c\ year}$	=	26,001,752	(Btu/year)

where: $Q_{r\ month}$ = space heating requirement in Btu/month
SHF = fraction of the monthly space heating load supplied by solar energy (expressed as a decimal from fig. V-13 in chap. 5)

c. *Auxiliary Space Heating Requirement* (Q_{aux})

	$Q_{r\ month}$	−	$Q_{c\ month}$	=	Q_{aux} (Btu's)	
January	11,025,000	-	4,079,250	=	6,945,750	
February	8,751,400	-	4,025,644	=	4,725,756	
March	8,085,000	-	3,557,400	=	4,527,600	
April	5,262,600	-	1,210,398	=	4,052,202	
May	2,753,800	-	0	=	2,753,800	
June	838,000	-	0	=	838,000	
July	0	-	0	=	0	
August	58,800	-	58,800	=	0	
September	1,117,200	-	1,117,200	=	0	
October	4,155,200	-	3,407,264	=	747,936	
November	7,702,800	-	4,390,596	=	3,312,204	
December	10,388,000	-	4,155,200	=	6,232,800	
			$Q_{aux\ year}$	=	34,131,048	(Btu/year)

Combined system - Beryl, Utah

Step 1. Calculating Space Heat Loss

a. *Heat Loss Calculations*

Item	A	x	U		=	Btu/hr-°F
Trombe wall	199.5	x	.15		=	29.9
Exposed wall	435.2	x	.042		=	18.3
Exposed wall	567.8	x	.043		=	24.4
Roof	1423.5	x	.028		=	39.9
Door (exterior)	38.6	x	.33		=	12.7
Exposed glass	222.0	x	.49		=	108.8
Floor slab edge	P 126	x	F .17		=	21.4
Infiltration	V 15,030	x	n .67	x 0.018	=	180.5
			HL_{total}		=	435.9 Btu/hr-°F

where: A = exposed wall, floor, roof, door and glass area in square feet
U = overall coefficient of heat transmission in Btu/hr-sq ft-°F
P = perimeter length of floor slab edge in feet
F = edge loss factor from table V-3 in chapter 5
V = volume of the space in cubic feet
n = number of air changes per hour from table V-4 in chapter 5

b. *Calculating the Rate of Space Heat Loss per Square Foot of Floor Area (U_{sp})*

$$U_{sp} = \frac{HL_{total}}{A_{floor}} \times 24 \text{ hours} = \text{Btu/day-sq ft}_{floor}\text{-°F}$$

where: A_{floor} = floor area in square feet

$$U_{sp} = \frac{435.9}{1300} \times 24 = 8.05$$

Step 2. Calculating Space Heat Gain

a. Direct Solar Heat Gain

Item		A_{gl}	x	I_t	=	Btu/day	
Glass area	South	204	x	1457	=	297,228	
	SE, SW		x		=		
	East, West		x		=		
	NE, NW		x		=		
	North		x		=		
				HG_{sol}	=	297,228	Btu/day

where A_{gl} = surface area of the unshaded portion of the glazing in square feet
I_t = solar heat gain through one square foot of glazing in Btu/day

b. Heat Gain from a Thermal Storage Wall, Roof Pond or Attached Greenhouse

Item	A_{gl}	x	I_t	x	P	=	HG_{tm}	Btu/day
Collector area	199.5	x	1457	x	.52	=	151,149	Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet
I_t = solar heat gain through one square foot of glazing in Btu/day
P = percentage of incident energy on the face of a thermal wall or roof pond that is transferred to the space from figure V-6 in chapter 5

c. Calculating Space Heat Gain per Square Foot of Floor Area

$$HG_{sp} = \frac{HG_{sol}}{A_{floor}} + \frac{HG_{tm}}{A_{floor}} = \text{Btu/day-sq ft}_{floor}$$

where: A_{floor} = floor area in square feet

$$HG_{sp} = \frac{297,228}{1300} + \frac{151,149}{1300} = 345$$

Step 3. Determining Average Indoor Temperature

$$\text{daily average indoor temperature } (t_i) = \frac{HG_{sp}}{U_{sp}} + t_o$$

where: HG_{sp} = rate of space heat gain in Btu/day-sq ft_{floor}
U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
t_o = average daily outdoor temperature from Appendix G

$$t_i = \frac{345}{8.05} + 29.1 = 72^{\circ}F$$

Step 4. Determining Daily Space Temperature Fluctuations

See chapter 5, Fine Tuning

Step 5. Calculating Auxiliary Space Heating Requirements

a. Space Heating Requirements (Q_r)

	U_{sp}	x	A_{floor}	x	DD_{mo}	=	$Q_{r\ month}$ (Btu's)
January	8.05	x	1300	x	1125	=	11,773,125
February	8.05	x	1300	x	893	=	9,345,245
March	8.05	x	1300	x	825	=	8,633,625
April	8.05	x	1300	x	537	=	5,619,705
May	8.05	x	1300	x	281	=	2,940,665
June	8.05	x	1300	x	85	=	889,525
July	8.05	x	1300	x	0	=	0
August	8.05	x	1300	x	6	=	62,790
September	8.05	x	130C	x	114	=	1,193,010
October	8.05	x	1300	x	424	=	4,437,160
November	8.05	x	1300	x	786	=	8,225,490
December	8.05	x	1300	x	1060	=	11,092,900
					$Q_{r\ year}$	=	64,213,240 (Btu/year)

where: U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
A_{floor} = floor area in square feet
DD_{mo} = degree days per month

b. Solar Heating Contribution for Direct Gain Systems, Thermal Storage Walls and Roof Ponds (Q_c)

	$Q_{r\ month}$	x	solar heating fraction (SHF)	=	$Q_{c\ month}$ (Btu's)
January	11,773,125	x	.58	=	6,828,413
February	9,345,245	x	.67	=	6,261,314
March	8,633,625	x	.67	=	5,784,529
April	5,619,705	x	.52	=	2,922,247
May	2,940,665	x	.24	=	705,760
June	889,525	x	0	=	0
July	0	x	0	=	0
August	62,790	x	1.00	=	62,790
September	1,193,010	x	1.00	=	1,193,010
October	4,437,160	x	.94	=	4,170,930
November	8,225,490	x	.77	=	6,333,627
December	11,092,900	x	.60	=	6,655,740
			$Q_{c\ year}$	=	40,918,360 (Btu/year)

where $Q_{r\ month}$ = space heating requirement in Btu/month
SHF = fraction of the monthly space heating load supplied by solar energy (expressed as a decimal from fig. V-13 in chap. 5)

c. Auxiliary Space Heating Requirement (Q_{aux})

	$Q_{r\ month}$	—	$Q_{c\ month}$	=	Q_{aux} (Btu's)
January	11,773,125	-	6,828,413	=	4,944,712
February	9,345,245	-	6,261,314	=	3,083,931
March	8,633,625	-	5,784,529	=	2,849,096
April	5,619,705	-	2,922,247	=	2,697,458
May	2,940,665	-	705,760	=	2,234,905
June	889,525	-	0	=	889,525
July	0	-	0	=	0
August	62,790	-	62,790	=	0
September	1,193,010	-	1,193,010	=	0
October	4,437,160	-	4,170,930	=	266,230
November	8,225,490	-	6,333,627	=	1,891,863
December	11,092,900	-	6,655,740	=	4,437,160
			$Q_{aux\ year}$	=	23,294,880 (Btu/year)

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Direct gain - Ely, Nevada

Step 1. Calculating Space Heat Loss

a. Heat Loss Calculations

Item	A	x	U	=	Btu/hr-°F
Exposed wall	405.8	x	.042	=	17.0
Exposed wall	635.8	x	.043	=	27.3
Exposed wall		x		=	
Roof	1371.0	x	.028	=	38.4
Door (exterior)	38.6	x	.33	=	12.7
Exposed glass	293.0	x	.49	=	143.6
Floor slab edge	P 125	x	F .17	=	21.3
Infiltration	V 13,655	x	n .67 x 0.018	=	163.9
			HL_{total}	=	424.2 Btu/hr-°F

where: A = exposed wall, floor, roof, door and glass area in square feet
U = overall coefficient of heat transmission in Btu/hr-sq ft-°F
P = perimeter length of floor slab edge in feet
F = edge loss factor from table V-3 in chapter 5
V = volume of the space in cubic feet
n = number of air changes per hour from table V-4 in chapter 5

b. Calculating the Rate of Space Heat Loss per Square Foot of Floor Area (U_{sp})

$$U_{sp} = \frac{HL_{total}}{A_{floor}} \times 24 \text{ hours} = \text{Btu/day-sq ft}_{floor}\text{-°F}$$

where: A_{floor} = floor area in square feet

$$U_{sp} = \frac{424.2}{1250} \times 24 = 8.14$$

Step 2. Calculating Space Heat Gain

a. *Direct Solar Heat Gain*

Item		A_{gl}	x	I_t	=	Btu/day
Glass area	South	275	x	1416	=	389,400
	SE, SW		x		=	
	East, West		x		=	
	NE, NW		x		=	
	North		x		=	
				HG_{sol}	=	389,400 Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet

I_t = solar heat gain through one square foot of glazing in Btu/day

b. *Heat Gain from a Thermal Storage Wall, Roof Pond or Attached Greenhouse*

Item	A_{gl}	x	I_t	x	P	=	HG_{tm}	Btu/day
Collector area		x		x		=		Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet

I_t = solar heat gain through one square foot of glazing in Btu/day

P = percentage of incident energy on the face of a thermal wall or roof pond that is transferred to the space from figure V-6 in chapter 5

c. *Calculating Space Heat Gain per Square Foot of Floor Area*

$$HG_{sp} = \frac{HG_{sol}}{A_{floor}} + \frac{HG_{tm}}{A_{floor}} = \text{Btu/day-sq ft}_{floor}$$

where: A_{floor} = floor area in square feet

$$HG_{sp} = \frac{389{,}400}{1250} + 0 = 311.5$$

Step 3. Determining Average Indoor Temperature

$$\text{daily average indoor temperature } (t_i) = \frac{HG_{sp}}{U_{sp}} + t_o$$

where: HG_{sp} = rate of space heat gain in Btu/day-sq ft_{floor}
U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
t_o = average daily outdoor temperature from Appendix G

$$t_i = \frac{311.5}{8.14} + 27.3 = 65.6^{o}F$$

Step 4. Determining Daily Space Temperature Fluctuations

See chapter 5, Fine Tuning

Step 5. Calculating Auxiliary Space Heating Requirements

a. *Space Heating Requirements (Q_r)*

	U_{sp}	x	A_{floor}	x	DD_{mo}	=	$Q_{r\ month}$ (Btu's)
January	8.14	x	1250	x	1283	=	13,054,525
February	8.14	x	1250	x	1039	=	10,571,825
March	8.14	x	1250	x	998	=	10,154,650
April	8.14	x	1250	x	711	=	7,234,425
May	8.14	x	1250	x	470	=	4,782,250
June	8.14	x	1250	x	241	=	2,452,175
July	8.14	x	1250	x	23	=	234,025
August	8.14	x	1250	x	62	=	630,850
September	8.14	x	1250	x	265	=	2,696,375
October	8.14	x	1250	x	589	=	5,993,075
November	8.14	x	1250	x	930	=	9,462,750
December	8.14	x	1250	x	1203	=	12,240,525
					$Q_{r\ year}$	=	79,507,450 (Btu/year)

where: U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
A_{floor} = floor area in square feet
DD_{mo} = degree-days per month

b. Solar Heating Contribution for Direct Gain Systems, Thermal Storage Walls and Roof Ponds (Q_c)

	$Q_{r\ month}$	x	solar heating fraction (SHF)	=	$Q_{c\ month}$ (Btu's)	
January	13,054,525	x	.38	=	4,960,720	
February	10,571,825	x	.46	=	4,863,040	
March	10,154,650	x	.44	=	4,468,046	
April	7,234,425	x	.22	=	1,591,574	
May	4,782,250	x	0	=	0	
June	2,452,175	x	0	=	0	
July	234,025	x	0	=	0	
August	630,850	x	.97	=	611,925	
September	2,696,375	x	.89	=	2,399,774	
October	5,993,075	x	.75	=	4,494,806	
November	9,462,750	x	.56	=	5,299,140	
December	12,240,525	x	.40	=	4,896,210	
			$Q_{c\ year}$	=	33,585,235	(Btu/year)

where: $Q_{r\ month}$ = space heating requirement in Btu/month
SHF = fraction of the monthly space heating load supplied by solar energy (expressed as a decimal from fig. V-13 in chap. 5)

c. Auxiliary Space Heating Requirement (Q_{aux})

	$Q_{r\ month}$	—	$Q_{c\ month}$	=	Q_{aux} (Btu's)	
January	13,054,525	-	4,960,720	=	8,093,805	
February	10,571,825	-	4,863,040	=	5,708,785	
March	10,154,650	-	4,468,046	=	5,686,604	
April	7,234,425	-	1,591,574	=	5,642,851	
May	4,782,250	-	0	=	4,782,250	
June	2,452,175	-	0	=	2,452,175	
July	234,025	-	0	=	234,025	
August	630,850	-	611,925	=	18,925	
September	2,696,375	-	2,399,774	=	296,601	
October	5,993,075	-	4,494,806	=	1,498,269	
November	9,462,750	-	5,299,140	=	4,163,610	
December	12,240,525	-	4,896,210	=	7,344,315	
			$Q_{aux\ year}$	=	45,922,215	(Btu/year)

Combined system - Ely, Nevada

Step 1. Calculating Space Heat Loss

a. Heat Loss Calculations

Item	A	x	U		=	Btu/hr-°F
Trombe wall	199.5	x	.15		=	29.9
Exposed wall	447.9	x	.042		=	18.8
Exposed wall	571.1	x	.043		=	24.6
Roof	1423.5	x	.028		=	39.9
Door (exterior)	38.6	x	.33		=	12.7
Exposed glass	237.0	x	.49		=	116.1
Floor slab edge	P 126	x	F .17		=	21.4
Infiltration	V 15,195	x	n .67	x 0.018	=	182.3
				HL_{total}	=	445.7 Btu/hr-°F

where: A = exposed wall, floor, roof, door and glass area in square feet
U = overall coefficient of heat transmission in Btu/hr-sq ft-°F
P = perimeter length of floor slab edge in feet
F = edge loss factor from table V-3 in chapter 5
V = volume of the space in cubic feet
n = number of air changes per hour from table V-4 in chapter 5

b. Calculating the Rate of Space Heat Loss per Square Foot of Floor Area (U_{sp})

$$U_{sp} = \frac{HL_{total}}{A_{floor}} \times 24 \text{ hours} = \text{Btu/day-sq ft}_{floor}\text{-°F}$$

where: A_{floor} = floor area in square feet

$$U_{sp} = \frac{445.7}{1300} \times 24 = 8.23$$

Step 2. Calculating Space Heat Gain

a. Direct Solar Heat Gain

Item		A_{gl}	x	I_t	=	Btu/day
Glass area	South	219	x	1416	=	310,104
	SE, SW		x		=	
	East, West		x		=	
	NE, NW		x		=	
	North		x		=	
				HG_{sol}	=	310,104 Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet
I_t = solar heat gain through one square foot of glazing in Btu/day

b. Heat Gain from a Thermal Storage Wall, Roof Pond or Attached Greenhouse

Item	A_{gl}	x	I_t	x	P	=	HG_{tm}	Btu/day
Collector area	199.5	x	1416	x	.52	=	146,896	Btu/day

where: A_{gl} = surface area of the unshaded portion of the glazing in square feet
I_t = solar heat gain through one square foot of glazing in Btu/day
P = percentage of incident energy on the face of a thermal wall or roof pond that is transferred to the space from figure V-6 in chapter 5

c. Calculating Space Heat Gain per Square Foot of Floor Area

$$HG_{sp} = \frac{HG_{sol}}{A_{floor}} + \frac{HG_{tm}}{A_{floor}} = \text{Btu/day-sq ft}_{floor}$$

where: A_{floor} = floor area in square feet

$$HG_{sp} = \frac{310,104}{1300} + \frac{146,896}{1300} = 352$$

Step 3. Determining Average Indoor Temperature

$$\text{daily average indoor temperature } (t_i) = \frac{HG_{sp}}{U_{sp}} + t_o$$

where: HG_{sp} = rate of space heat gain in Btu/day-sq ft_{floor}
U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
t_o = average daily outdoor temperature from Appendix G

$$t_i = \frac{352}{8.23} + 27.3 = 70.1^{o}F$$

Step 4. Determining Daily Space Temperature Fluctuations

See chapter 5, Fine Tuning

Step 5. Calculating Auxiliary Space Heating Requirements

a. Space Heating Requirements (Q_r)

	U_{sp}	x	A_{floor}	x	DD_{mo}	=	$Q_{r\ month}$ (Btu's)
January	8.23	x	1300	x	1283	=	13,726,817
February	8.23	x	1300	x	1039	=	11,116,261
March	8.23	x	1300	x	998	=	10,677,602
April	8.23	x	1300	x	711	=	7,606,989
May	8.23	x	1300	x	470	=	5,028,530
June	8.23	x	1300	x	241	=	2,578,459
July	8.23	x	1300	x	23	=	246,077
August	8.23	x	1300	x	62	=	663,338
September	8.23	x	1300	x	265	=	2,835,235
October	8.23	x	1300	x	589	=	6,301,711
November	8.23	x	1300	x	930	=	9,950,070
December	8.23	x	1300	x	1203	=	12,870,897
					$Q_{r\ year}$	=	83,601,986 (Btu/year)

where: U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
A_{floor} = floor area in square feet
DD_{mo} = degree-days per month

b. Solar Heating Contribution for Direct Gain Systems, Thermal Storage Walls and Roof Ponds (Q_c)

	$Q_{r\ month}$	x	solar heating fraction (SHF)	=	$Q_{c\ month}$ (Btu's)	
January	13,726,817	x	.56	=	7,687,018	
February	11,116,261	x	.65	=	7,225,570	
March	10,677,602	x	.62	=	6,620,113	
April	7,606,989	x	.43	=	3,271,005	
May	5,028,530	x	.17	=	854,850	
June	2,578,459	x	0	=	0	
July	246,077	x	1.00	=	246,077	
August	663,338	x	1.00	=	663,338	
September	2,835,235	x	.97	=	2,750,178	
October	6,301,711	x	.89	=	5,608,523	
November	9,950,070	x	.73	=	7,263,551	
December	12,870,897	x	.60	=	7,722,538	
			$Q_{c\ year}$	=	49,912,761	(Btu/year)

where: $Q_{r\ month}$ = space heating requirement in Btu/month
SHF = fraction of the monthly space heating load supplied by solar energy (expressed as a decimal from fig. V-13 in chap. 5)

c. Auxiliary Space Heating Requirement (Q_{aux})

	$Q_{r\ month}$	—	$Q_{c\ month}$	=	Q_{aux} (Btu's)	
January	13,726,817	-	7,687,018	=	6,039,799	
February	11,116,261	-	7,225,570	=	3,890,691	
March	10,677,602	-	6,620,113	=	4,057,489	
April	7,606,989	-	3,271,005	=	4,335,984	
May	5,028,530	-	854,850	=	4,173,680	
June	2,578,549	-	0	=	2,578,459	
July	246,077	-	246,077	=	0	
August	663,338	-	663,338	=	0	
September	2,835,235	-	2,750,178	=	85,057	
October	6,301,711	-	5,608,523	=	693,188	
November	9,950,070	-	7,263,551	=	2,686,519	
December	12,870,897	-	7,722,538	=	5,148,359	
			$Q_{aux\ year}$	=	33,689,225	(Btu/year)

Conventional Structure - Beryl, Utah

Step 1. Calculating Space Heat Loss

a. Heat Loss Calculations

Item	A	x	U		=	Btu/hr-°F
Exposed wall	891.4	x	.043		=	38.3
Exposed wall		x			=	
Exposed wall		x			=	
Roof	1250	x	.030		=	37.5
Door (exterior)	38.6	x	.33		=	12.7
Exposed glass	70	x	.49		=	34.3
Floor slab edge	P 125	x	F 17		=	21.3
Infiltration	V 10,000	x	n .67	x 0.018	=	120.0
			HL_{total}		=	266.1 Btu/hr-°F

where: A = exposed wall, floor, roof, door and glass area in square feet
U = overall coefficient of heat transmission in Btu/hr-sq ft-°F
P = perimeter length of floor slab edge in feet
F = edge loss factor from table V-3 in chapter 5
V = volume of the space in cubic feet
n = number of air changes per hour from table V-4 in chapter 5

b. Calculating the Rate of Space Heat Loss per Square Foot of Floor Area (U_{sp})

$$U_{sp} = \frac{HL_{total}}{A_{floor}} \times 24 \text{ hours} = \text{Btu/day-sq ft}_{floor}\text{-°F}$$

where: A_{floor} = floor area in square feet

$$U_{sp} = \frac{266.1}{1250} \times 24 = 5.07$$

Step 3. Determining Average Indoor Temperature

$$\text{daily average indoor temperature } (t_i) = \frac{HG_{sp}}{U_{sp}} + t_o$$

where: HG_{sp} = rate of space heat gain in Btu/day-sq ft_{floor}
U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
t_o = average daily outdoor temperature from Appendix G

Step 4. Determining Daily Space Temperature Fluctuations

See chapter 5, Fine Tuning

Step 5. Calculating Auxiliary Space Heating Requirements

a. *Space Heating Requirements (Q_r)*

	U_{sp}	x	A_{floor}	x	DD_{mo}	=	$Q_{r\ month}$ (Btu's)
January	5.07	x	1250	x	1125	=	7,129,688
February	5.07	x	1250	x	893	=	5,659,388
March	5.07	x	1250	x	825	=	5,228,438
April	5.07	x	1250	x	537	=	3,403,238
May	5.07	x	1250	x	281	=	1,780,838
June	5.07	x	1250	x	85	=	538,688
July	5.07	x	1250	x	0	=	0
August	5.07	x	1250	x	6	=	38,025
September	5.07	x	1250	x	114	=	722,475
October	5.07	x	1250	x	424	=	2,687,100
November	5.07	x	1250	x	786	=	4,981,275
December	5.07	x	1250	x	1060	=	6,717,750
					$Q_{r\ year}$	=	38,886,903 (Btu/year)

where: U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
A_{floor} = floor area in square feet
DD_{mo} = degree-days per month

Conventional Structure - Ely, Nevada

Step 1. Calculating Space Heat Loss

a. Heat Loss Calculations

Item	A	x	U		=	Btu/hr-°F
Exposed wall	891.4	x	.043		=	38.3
Exposed wall		x			=	
Exposed wall		x			=	
Roof	1250	x	.030		=	37.5
Door (exterior)	38.6	x	.33		=	12.7
Exposed glass	70	x	.49		=	34.3
Floor slab edge	P 125	x	F 17		=	21.3
Infiltration	V 10,000	x	n .67	x 0.018	=	120.0
				HL_{total}	=	266.1 Btu/hr-°F

where: A = exposed wall, floor, roof, door and glass area in square feet
U = overall coefficient of heat transmission in Btu/hr-sq ft-°F
P = perimeter length of floor slab edge in feet
F = edge loss factor from table V-3 in chapter 5
V = volume of the space in cubic feet
n = number of air changes per hour from table V-4 in chapter 5

b. Calculating the Rate of Space Heat Loss per Square Foot of Floor Area (U_{sp})

$$U_{sp} = \frac{HL_{total}}{A_{floor}} \times 24 \text{ hours} = \text{Btu/day-sq ft}_{floor}\text{-°F}$$

where: A_{floor} = floor area in square feet

$$U_{sp} = \frac{266.1}{1250} \times 24 = 5.07$$

Step 3. Determining Average Indoor Temperature

$$\text{daily average indoor temperature } (t_i) = \frac{HG_{sp}}{U_{sp}} + t_o$$

where: HG_{sp} = rate of space heat gain in Btu/day-sq ft_{floor}
U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
t_o = average daily outdoor temperature from Appendix G

Step 4. Determining Daily Space Temperature Fluctuations

See chapter 5, Fine Tuning

Step 5. Calculating Auxiliary Space Heating Requirements

a. Space Heating Requirements (Q_r)

	U_{sp}	x	A_{floor}	x	DD_{mo}	=	$Q_{r\ month}$ (Btu's)
January	5.07	x	1250	x	1283	=	8,131,013
February	5.07	x	1250	x	1039	=	6,584,663
March	5.07	x	1250	x	998	=	6,324,825
April	5.07	x	1250	x	711	=	4,505,963
May	5.07	x	1250	x	470	=	2,978,625
June	5.07	x	1250	x	241	=	1,527,338
July	5.07	x	1250	x	23	=	145,763
August	5.07	x	1250	x	62	=	392,925
September	5.07	x	1250	x	265	=	1,679,438
October	5.07	x	1250	x	589	=	3,732,788
November	5.07	x	1250	x	930	=	5,893,875
December	5.07	x	1250	x	1203	=	7,624,013
					$Q_{r\ year}$	=	49,521,229 (Btu/year)

where: U_{sp} = rate of space heat loss in Btu/day-sq ft_{floor}-°F
A_{floor} = floor area in square feet
DD_{mo} = degree-days per month

APPENDIX D

DIFFERENTIAL INITIAL INVESTMENT COST COMPUTATIONS

Direct Gain - Beryl, Utah

Exterior Wall (Includes common wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	674.8	SF	.40	270.
Stucco	75.0	SY	22.90	1718.
3/4" Plywood	674.8	SF	.78	526.
Fiber Board	674.8	SF	.58	391.
Framing	1131.9	FBM	.865	979.
Insulation	674.8	SF	1.38	931.
Gypsum Board	947.9	SF	.40	379.
Paint	947.9	SF	.40	379.
2' x 4' Window	1	Ea	151.00	151.
2' x 3' Window	1	Ea	130.00	130.
4' x 7' Window	2	Ea	222.00	444.
4' x 6' Window	5	Ea	196.00	980.
4' x 8' Window	1	Ea	248.00	248.
3' x 4' Window	10	Ea	138.00	1380.

Sub-Total = $8906.

Exterior Wall (Mass wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	406.2	SF	.40	162.
Stucco	45.1	SY	22.90	1033.
3/4" Plywood	406.2	SF	.78	317.
Fiber Board	406.2	SF	.58	236.
Framing	359.5	FBM	.865	311.
Insulation	406.2	SF	1.38	561.
Brick	406.2	SF	11.28	4582.
3' x 4' Window	1	Ea	138.00	138.

Sub-Total = $7340.

Foundation

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Floor	15.3	CY	145.00	2219.
Footing	26.9	CY	155.00	4170.
Masonry Tile	1250	SF	3.61	4513.

Sub-Total = $10,902.

Roof

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	1371	SF	.40	548.
Support Beam	200	FBM	1.025	205.
Gypsum Board	1371	SF	.35	480.
Rafters	2074.8	FBM	.715	1484.
Bridging	950	LF	.58	551.
Insulation	1371	SF	.56	768.
3/4" Plywood	1660	SF	.78	1295.
Felt	16.6	SQ	9.50	158.
Asphalt Shingles	16.6	SQ	61.00	1013.
Fascia Board	187.9	FBM	1.50	282.
1/2" Plywood	375.8	SF	.62	233.
Paint	563.7	SF	.40	225.

Sub-Total = $7242.

Heating System

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Natural gas furnace	1	Ea	715.00	715.
Electrical resistance heater	1	Ea	445.00	445.

(Natural gas) Grand Total=$35,105.
(Electric) Grand Total=$34,835.

Combined System - Beryl, Utah

Exterior Wall (Includes common wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	567.8	SF	.40	227.
Stucco	63.1	SY	22.90	1445.
3/4" Plywood	567.8	SF	.78	443.
Fiber Board	567.8	SF	.58	329.
Framing	1090.5	SF	.865	943.
Insulation	1003	SF	1.38	1384.
Gypsum Board	868.4	SF	.40	347.
Paint	868.4	SF	.40	347.
Brick	199.5	SF	16.51	3294.
2' x 3' Window	1	Ea	130.00	130.
2' x 6' Window	7	Ea	138.00	966.
2.75' x 8.75' Window	5	Ea	196.00	980.
4.75' x 6' Window	7	Ea	225.00	1515.

Sub-Total = $12,410.

Exterior Wall (Mass wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	435.2	SF	.40	174.
Stucco	48.4	SY	22.90	1108.
3/4" Plywood	435.2	SF	.78	339.
Fiber Board	435.2	SF	.58	252.
Framing	376.1	FBM	.865	325.
Insulation	435.2	SF	1.38	601.
Brick	435.2	SF	11.28	4909.
3' x 4' Window	1	Ea	138.00	138.

Sub-Total = $7846.

Foundation

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Floor	15.9	CY	145.00	2306.
Footing	29.5	CY	155.00	4573.
Vinyl Tile	1250	SF	3.06	3825.
Adhesive	7	Gal	7.70	54.

Sub-Total = $10,758.

Roof

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	1388	SF	.40	555.
Support Beam	200	FBM	1.025	205.
Gypsum Board	1388	SF	.35	486.
Rafters	2161.1	FBM	.715	1545.
Bridging	950	LF	.58	551.
Insulation	1388	SF	.56	777.
3/4" Plywood	1725.4	SF	.78	1346.
Felt	16.9	SQ	9.50	160.
Asphalt Shingles	16.9	SQ	61.00	1030.
Fascia Board	189.2	FBM	1.50	284.
1/2" Plywood	378.4	SF	.62	235.
Paint	567.6	SF	.40	227.

Sub-Total = $7401.

Heating System

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Natural gas furnace	1	Ea	715.00	715.
Electrical resistance heater	1	Ea	445.00	445.

(Natural gas) Grand Total = $39,130.
(Electric) Grand Total = $38,860.

Direct Gain - Ely, Nevada

Exterior Wall (Includes common wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	639.8	SF	.40	256.
Stucco	71.1	SY	22.90	1628.
3/4" Plywood	639.8	SF	.78	499.
Fiber Board	639.8	SF	.58	371.
Framing	1095.8	FBM	.865	948.
Insulation	639.8	SF	1.38	883.
Gypsum Board	912.9	SF	.40	365.
Paint	912.9	SF	.40	365.
4' x 7' Window	5	Ea	222.00	1110.
3' x 5' Window	9	Ea	140.00	1260.
2' x 3' Window	1	Ea	130.00	130.

Sub-Total = $7815.

Exterior Wall (Mass wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	406.2	SF	.40	162.
Stucco	45.1	SY	22.90	1033.
3/4" Plywood	406.2	SF	.78	317.
Fiber Board	406.2	SF	.58	236.
Framing	261.5	FBM	.865	226.
Insulation	406.2	SF	1.38	561.
Brick	406.2	SF	11.28	4582.
3' x 4' Window	1	Ea	138.00	138.

Sub-Total = $7255.

Foundation

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Floor	15.3	CY	145.00	2219.
Footing	26.9	CY	155.00	4170.
Masonry Tile	1250	SF	3.61	4513.

Sub-Total = $10,902.

Roof

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	1371	SF	.40	548.
Support Beam	200	FBM	1.025	205.
Gypsum Board	1371	SF	.35	480.
Rafters	2074.8	FBM	.715	1484.
Bridging	950	LF	.58	551.
Insulation	1371	SF	.56	768.
3/4" Plywood	1660	SF	.78	1295.
Felt	16.6	SQ	9.50	158.
Asphalt Shingles	16.6	SQ	61.00	1013.
Fascia Board	187.9	FBM	1.50	282.
1/2" Plywood	375.8	SF	.62	233.
Paint	563.7	SF	.40	225.

Sub-Total = $7242.

Heating System

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Natural gas furnace	1	Ea	715.00	715.
Electrical resistance heater	1	Ea	445.00	445.

(Natural gas) Grand Total = $33,929.
(Electric) Grand Total = $33,659.

Combined System - Ely, Nevada

Exterior Wall (Includes common wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	571.1	SF	.40	228.
Stucco	63.5	SY	22.90	1454.
3/4" Plywood	571.1	SF	.78	445.
Fiber Board	571.1	SF	.58	331.
Framing	1202	FBM	.865	1040.
Insulation	571.1	SF	1.38	788.
Gypsum Board	875	SF	.40	350.
Paint	875	SF	.40	350.
Brick	199.5	SF	16.51	3294.
2' x 3' Window	1	Ea	130.00	130.
2' x 6' Window	7	Ea	138.00	966.
4.75' x 6' Window	7	Ea	225.00	1575.
3' x 5' Window	9	Ea	140.00	1260.

Sub-Total = $12,211.

Exterior Wall (Mass wall)

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	447.9	SF	.40	179.
Stucco	49.8	SY	22.90	1140.
3/4" Plywood	447.9	SF	.78	349.
Fiber Board	447.9	SF	.58	260.
Framing	383.3	FBM	.865	332.
Insulation	447.9	SF	1.38	618.
Brick	447.9	SF	11.28	5052.
3' x 4' Window	1	Ea	138.00	138.

Sub-Total = $8068.

Foundation

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Floor	15.9	CY	145.00	2306.
Footing	29.5	CY	155.00	4573.
Vinyl Tile	1250	SF	3.06	3825.
Adhesive	7	Gal	7.70	54.

Sub-Total = $10,758.

Roof

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	1388	SF	.40	555.
Support Beam	200	FBM	1.025	205.
Gypsum Board	1388	SF	.35	486.
Rafters	2161.1	FBM	.715	1545.
Bridging	950	LF	.58	551.
Insulation	1388	SF	.56	777.
3/4" Plywood	1725.4	SF	.78	1346.
Felt	16.9	SQ	9.50	160.
Asphalt Shingles	16.9	SQ	61.00	1030.
Fascia Board	189.2	FBM	1.50	284.
1/2" Plywood	378.4	SF	.62	235.
Paint	567.6	SF	.40	227.

Sub-Total = $7401.

Heating System

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Natural gas furnace	1	Ea	715.00	715.
Electrical resistance heater	1	Ea	445.00	445.

(Natural gas) Grand Total = $39,153.
(Electric) Grand Total = $38,883.

Conventional - Beryl, Utah and Ely, Nevada

Exterior Wall

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	943.5	SF	.40	377.
Stucco	104.8	SY	22.90	2401.
3/4" Plywood	943.5	SF	.78	736.
Fiber Board	943.5	SF	.58	547.
Framing	1109	FBM	.865	959.
Insulation	891.4	SF	1.38	1230.
Gypsum Board	1091.4	SF	.40	437.
Paint	1091.4	SF	.40	437.
2' x 3' Window	1	Ea	130.00	130.
4' x 5' Window	2	Ea	177.00	354.
3' x 4' Window	2	Ea	138.00	276.

Sub-Total = $7884.

Foundation

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Floor	15.3	CY	145.00	2219.
Footing	20.4	CY	155.00	3162.
Vinyl Tile	1250	SF	3.06	3825.
Adhesive	7	Gal	7.70	54.

Sub-Total = $9260.

Roof

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Paint	1250	SF	.40	500.
Gypsum Board	1250	SF	.35	438.
Bridging	1850	LF	.58	1073.
Roof Trusses	1250	SF	1.17	1463.
Insulation	1250	SF	.56	700.
3/4" Plywood	1535	SF	.78	1197.
Felt	15.35	SQ	61.00	936.
Asphalt Shingles	15.35	SQ	9.50	146.
Fascia Board	65.2	FBM	1.25	82.
Soffitt Framing	28.3	FBM	.865	24.
1/2" Plywood	190.7	SF	.68	130.
Paint	255.9	SF	.40	102.

Sub-Total = $6791.

Heating System - Beryl, Utah

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Natural gas furnace	1	Ea	715.00	715.
Electrical resistance heater	1	Ea	325.00	325.

Heating System - Ely, Nevada

COMPONENT	QUANTITY	UNIT	PRICE/COST UNIT ($)	($)
Natural gas furnace	1	Ea	715.00	715.
Electrical resistance heater	1	Ea	445.00	445.

Beryl, Utah

(Natural gas) Grand Total = $24,650.
(Electric) Grand Total = $24,260.

Ely, Nevada

(Natural gas) Grand Total = $24,650.
(Electric) Grand Total = $24,380.

APPENDIX E

LIFE-CYCLE COST ANALYSES
COMPUTATIONS

This appendix contains the intermediate computations involved in the determination of the life-cycle costs for each MFH design. The computations were accomplished in accordance with the guidance in the Life-Cycle Costing Manual for the Federal Energy Management Programs. The following equation was used for determination of life-cycle costs (LCC):

$$LCC = (.90)(I_{costs}) + P_e$$

where:

I_{costs} = the differential investment costs of a design

P_e = the value of yearly energy costs in baseline year dollars brought back to the start of the project.

The P_e costs were computed by the equation:

$$P_e = E_c\,[e_c(1+e)^{n_{ps}}](P/A,(7-e_2),n_2) + E_c\,[e_c(1+e)^{n_{ps}}](P/A,(7-e_3),n_3)(P/F,(7-e_2),n_2)$$

where:

E_c = energy price for the baseline year*

e = escalation rate from Table C-6

e_c = energy used yearly in MBtu

e_2 = escalation rate for mid-1985 to mid-1990 (Table C-7)

e_3 = escalation rate for mid-1990 to mid-1995 and beyond (Table C-8)

n_{ps} = number of years from feasibility study to the project start

n_2 = number of years of project life within mid-1985 to mid-1990 period

n_3 = number of years of project life beyond mid-1990.

*NOTE: Energy prices used for this study were based on 1980 energy prices from Table C-1. These prices should be based on 1981 prices. However, at the time of this study these prices were not available.

Direct Gain - Beryl, Utah

Electricity

$$P_e = [17.46(34.1)\ (1+(-.0002))^4]\ (P/A,7-(-2.96),5)$$
$$+[17.46(34.1)(1+(-.0002))^4]\ (P/A,7-(-2.70),20)$$
$$(P/F,\ 7-(-2.96),5)$$

$$P_e = [594.9](P/A,9.96,5)+[594.9](P/A,9.70,20)(P/F,9.96,5)$$

$$P_e = [594.9](3.79)+[594.9](8.69)(.622) = \$5471.$$

LCC = (.90)($34,835) + $5471. = $36,823.

Natural gas

$$P_e = [3.37(34.1)(1+(.0175))^4](P/A,7-(4.42),5)$$
$$+[3.37(34.1)(1+(.0175))^4](P/A,7-(1.38),20)$$
$$(P/F,\ 7-(4.42),5)$$

$$P_e = [123.2](P/A,2.78,5)+[123.2](P/A,5.62,20)(P/F,2.78,5)$$

$$P_e = [123.2](4.61) + [123.2]\ (11.83)(.872) = \$1839.$$

LCC = (.90)($35,105) + $1839. = $33,434.

Combined System - Beryl, Utah

Electricity

$$P_e = [17.46(23.3)(1+(-.0002))^4](3.79)$$
$$+[17.46(23.3)(1+(-.0002))^4](8.69)(.622)$$

$$P_e = [406.5](3.79) + [406.5](8.69)(.622) = \$3738.$$

LCC = (.90)($38,860.) + $3738. = $38,712.

Natural gas

$$P_e = [3.37(23.3)(1+(.0175))^4](4.61)$$
$$+[3.37(23.3)(1+(.0175))^4](11.83)(.872)$$

$$P_e = [84.2]\ 4.61 + [84.2]\ (11.83)(.872) = \$1257.$$

LCC = (.90)($39,130.) + $1257. = $36,474.

Conventional Design - Beryl, Utah

Electricity

$$P_e = [17.46(38.9)(1+(-.0002))^4](3.79)$$
$$+[17.46(38.9)(1+(-.0002))^4](8.69)(.622)$$

$$P_e = [678.7](3.79) + [678.7](8.69)(.622) = \$6241.$$

$$LCC = (.90)(\$24{,}260.) + \$6{,}241. = \$28{,}075.$$

Natural gas

$$P_e = [3.37(38.9)(1+(.0175))^4](4.61)$$
$$+[3.37(38.9)(1+(.0175))^4](11.83)(.872)$$

$$P_e = [140.5]\ (4.61) + [140.5]\ (11.83)(.872) = \$2097.$$

$$LCC = (.90)(\$24{,}650.) + \$2097. = \$24{,}282.$$

Direct Gain - Ely, Nevada

Electricity

$$P_e = [21.25(45.9)(1+(-.0001))^4](P/A,\ 7-(.43),5)$$
$$+[21.25(45.9)(1+(-.0001))^4](P/A,\ 7-(-2.21),20)$$
$$(P/F,\ 7-(.43),5)$$

$$P_e = [975](P/A,6.57,5)+[975](P/A,9.21,20)(P/F,6.57,5)$$

$$P_e = [975](4.15) + [975](8.99)(.727) = \$10,418.$$

$$LCC = (.90)(\$33,659.) + \$10,418. = \$40,711.$$

Natural gas

$$P_e = [3.76(45.9)(1+(.0176))^4](P/A,\ 7-(1.66),5)$$
$$+[3.76(45.9)(1+(.0176))^4](P/A,\ 7-(.29),20)$$
$$(P/F,\ 7-(1.66),5)$$

$$P_e = [185.1](P/A,5.34,5) + [185.1](P/A,6.71,20)(P/F,5.34,5)$$

$$P_e = [185.1](4.29) + [185.1](10.84)(.77) = \$2339.$$

$$LCC = (.90)(\$33,929.) + \$2339. = \$32,875.$$

Combined System - Ely, Nevada

Electricity

$$P_e = [21.25(33.7)(1+(-.0001))^4](4.15)$$
$$+[21.25(33.7)(1+(-.0001))^4](8.99)(.727)$$

$$P_e = (715.8)(4.15) + (715.8)(8.99)(.727) = \$7649.$$

LCC = (.90)($38,885.) + $7649. = $42,646.

Natural gas

$$P_e = [3.76(33.7)(1+(.0176))^4](4.29)$$
$$+[3.76(33.7)(1+(.0176))^4](10.84)(.77)$$

$$P_e = (135.9)(4.29) + (135.9)(10.84)(.77) = \$1717.$$

LCC = (.90)($39,153.) + $1717. = $36,955.

Conventional Design - Ely, Nevada

Electricity

$$P_e = [21.25(49.5)(1+(-.0001))^4](4.15)$$
$$+[21.25(49.5)(1+(-.0001))^4](8.99)(.727)$$

$$P_e = (1051.5)(4.15) + (1051.5)(8.99)(.727) = \$11{,}236.$$

$$LCC = (.90)(\$24{,}380.) + \$11{,}236. = \$33{,}178.$$

Natural gas

$$P_e = [3.76(49.5)(1+(.0176))^4](4.29)$$
$$+[3.76(49.5)(1+(.0176))^4](10.84)(.77)$$

$$P_e = (199.6)(4.29) + (199.6)(10.84)(.77) = \$2522.$$

$$LCC = (.90)(\$24{,}650.) + \$2522. = \$24{,}707.$$

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